UNITED STATES
NAVAL POSTGRADUATE SCHOOL

COMPRESSOR TEST RIG FOR INVESTIGATION OF FLOW PHENOMENA IN TURBO-MACHINES

---BY---

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A REPORT
TO THE NAVY DEPARTMENT
OFFICE OF NAVAL RESEARCH
UPON WORK CONDUCTED IN PART UNDER
ONR PROJECT NO. NR 061-058

FEB. 28, 1955

TECHNICAL REPORT NO. 12

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ABSTRACT

This report describes an experimental facility established at the U. S. Naval Postgraduate School, Department of Aeronautics, for research on phenomena of internal flow in turbo-machines, and describes some of the research problems that can be investigated with this equipment.

The facility consists essentially of a centrifugal blower of the mixed flow type, specially designed in regard to its aerodynamic and mechanical features, and highly instrumented to permit the thorough investigation of flow conditions at all important regions within the machine. The main feature of the design is the provision of means for measuring the pressure distribution along the surfaces of the rotating blades themselves.

The value of this machine for research lies in the fact that it supplies basic flow measurements not available otherwise, and provides a means of comparison between theory and experiment. It can, therefore, be an invaluable tool in the study of various specific research problems. Consequently, it should contribute to the development of a more adequate understanding of flow phenomena in turbo-machines.

The present report also includes detailed instructions for the automatic reduction and plotting of flow test data by means of the Model CRC 102A general purpose digital computer available at the Computations Center, U. S. Naval Postgraduate School.

Object of Report

The purposes of this report are:

1. to describe an experimental facility of the U. S. Naval Postgraduate School, Department of Aeronautics, for research on internal flow in turbo-machines.

2. to establish methods of experimental measurement and calculation of results.

3. to set up a system of designating pressure tap locations in the machine.

4. to indicate some of the research problems that can be investigated with this equipment.

Introduction

Although the principle of the gas turbine has been known for many years, it was not until 1939 that the first prime movers of this type were operating successfully. This lag between the inception of the idea and its practical achievement may be attributed in large measure to the lack of an adequate understanding of the fundamental aerodynamic processes which take place in turbo-machinery. It is only in the last two decades that the science of aerodynamics has advanced to the point where turbo-machines can be designed with efficiencies which bring the gas turbine into the realm of practical realization.

In all fields of application, however, there is a continued demand for higher standards of performance. This demand can be satisfied in the long run only by attaining a better understanding of the fundamental physical processes which underlie the operation of the turbo-machine. Among the most basic of the phenomena to be considered are those relating to the three dimensional flow of a real gas through stationary and rotating rows of blades. To improve performance over current levels, the present over-simplified flow theories based on one or two dimensional concepts, and on ignoring such important effects as those of viscosity, will first have to be replaced by more adequate formulations.

As in any other technical field, continued progress depends on maintaining a proper balance between theory and experiment. Theoretical concepts and experimental methods must be woven together. In particular, an advance in experimental method often brings with it a corresponding advance in theoretical conceptions, and this in turn may bring new possibilities of practical application.

The present experimental facility which has been established at the U. S. Naval Postgraduate School provides a research tool which offers the possibility of making significant contributions to our understanding of the basic phenomena of internal flow in turbo-machines.

The present apparatus consists essentially of an especially designed and highly instrumented test compressor. It is, therefore, possible to measure actual internal flow conditions in considerable detail throughout the entire machine for various overall operating conditions. This not only provides a means of studying qualitatively the detailed nature of the internal flow under different practical operating conditions, but also provides a quantitative comparison with the results of theoretical calculations.

It is hoped that in this way gradual progress can be made toward the establishment of flow theories which are sufficiently accurate to provide realistic methods of predicting performance.

The outstanding feature of the machine is the provision of a means for measuring pressures within the rotor itself, specifically at numerous points along the surfaces of the rotating blades. The flow through a rotating row of blades is significantly different from the flow through a similar row of stationary blades. Consequently, it is important to be able to carry out detailed flow measurements within the impeller itself. In this respect the present equipment fulfills a basic need.

Numerous pressure taps are also provided along the stationary walls and guide vanes.

The test rig was conceived in 1949 by Professor M. H. Vavra. The design and analysis was initially carried out by Professor Rudolph X. Meyer, and has been continued since 1952 by Professor T. H. Gawain. The design was worked out in its entirety by personnel of the Department of Aeronautics, who also planned and supervised the construction of the apparatus, and erected the test equipment. The program was carried out under the overall direction of Professor Vavra. The unit was ready for operation in August 1954.

Acknowledgements

The Department of Aeronautics, U. S. Naval Postgraduate School, gratefully acknowledges the active support and cooperation of the Office of Naval Research, Mechanics Branch, which sponsored and financed this project from its inception to June 1953.

The impellers were manufactured and tested by the U. S. Naval Aircraft Factory, Philadelphia. The cooperation and efforts of its personnel are greatly appreciated.

Special thanks are due to Mr. Norman Walker, Foreman of the Machine Shop of the Naval Postgraduate School, whose advice and skill greatly contributed to the successful erection of the test rig. Mr. Alvin Need and Mr. Paul McReynolds, draughtsmen and technicians, deserve thanks for faithfully carrying out the design and erection work.

The project could not have been accomplished without the support and encouragement of Professor W. M. Coates, Chairman of the Department of Aeronautics.

General Arrangement of the Machine

The general layout and arrangement of the various parts of the installation is shown in Figs. 1 through 10 at the end of the report.

These figures show the large size of the machine and its various components. The impeller is about 30 inches in diameter. The diffuser vanes measure approximately $6\frac{1}{2}$ inches in chord.

A large scale was chosen to insure the accuracy of the experimental measurements. Thus for given machining tolerances, the corresponding errors become relatively smaller as the size of the machine is increased. Disturbances in the flow, such as those due to the presence of pressure probes, tend to introduce less error into the overall flow pattern if other dimensions are relatively large. Furthermore, greater size permits the attainment of reasonable Reynolds numbers at moderate air velocities and rotational speeds. Moderate air velocities are preferable from the standpoint of accuracy of pressure measurement. Moderate rotational speeds are necessary for structural reasons.

Course of the Airflow and Measurement of the Flow Rate

The general operation of the machine is described by considering the course of the airflow through the system. As shown in Fig. 1, air is drawn into the machine uniformly along the circumference of the wooden frames #1 and #2 which form the two walls of the inlet passage. Its direction of flow is controlled by an annular row of guide vanes. These are shown in Fig. 5. Normally, the guide vanes are set radially. Their angular position may be changed as desired, however, so that it is possible to impart to the air a rotary motion or "prewhirl" in either direction.

As Fig. 1 shows, the inlet passage curves smoothly in such a way that the air is gradually turned from its original inward course to a direction parallel to the axis of the machine. At this point the air enters the impeller, whose general form is shown in Figs. 8 and 9.

The rotor consists of 23 blades cast integral with the hub and covered with a shroud. The center of the rotor is hollow. The hollow space contains the apparatus required to transmit the pressures created at various points along the surfaces of the rotating blades to stationary measuring instruments outside the machine. This pressure transmission apparatus is the central feature of the present installation and is decribed in more detail in a later section of this report.

It may be seen from Fig. 1 that the flow through the impeller changes from an axial direction at the inlet to a nearly radial direction at the outlet. The impeller also imparts a peripheral component of velocity to the air.

Upon leaving the impeller the air passes outward through an annular passage formed by the wooden walls of frames #3 and #4. These walls are smoothly curved in such a way that the air is gradually redirected into a plane perpendicular to the axis of the machine. Thereupon, the air passes through a row of stationary diffuser vanes. These are oriented so as to reduce the peripheral component of the air velocity. In passing through the diffuser the air undergoes an increase in pressure accompanied by a decrease in velocity.

The air is then discharged into a large annular plenum chamber. The plenum is the large outer structure shown in Fig. 3.

From the plenum the air passes into a long straight 24 inch diameter discharge pipe shown in Fig. 2. The air enters the pipe through a flow straightener grid. Approximately 18 pipe diameters downstream of the grid, a standard sharp edged orifice is placed into the line to serve as a means for measuring the mass flow rate through the machine. Details of the orifice installation are shown in Fig. 2. The method of calculating the flow rate is treated in Appendix I.

A short distance downstream of the orifice plate there is installed a throttle valve to regulate the rate of flow through the machine. Upon passing through the throttle valve, the air is discharged to the atmosphere.

Aerodynamic Features of the Impeller

The impeller somewhat resembles an ordinary centrifugal wheel. However, it has certain significant geometrical and aerodynamic features which distinguish it from the latter. In the usual centrifugal wheel, the flow channels are substantially radial over the greater part of the flow path. Furthermore, these wheels normally operate at relatively high peripheral speeds so that high centrifugal loads are imposed on the hub and blades. Consequently, the blades are necessarily made substantially radial as any appreciable deviation from this form would produce prohibitive bending stresses and deflections. However, while the radial blade provides a satisfactory solution of the stress problem, it presents a very severe restriction of the aerodynamic design. The purely radial blade has the undesirable characteristic that the aerodynamic loading on the blade tends to increase very rapidly toward the outlet. This causes the average direction of the relative flow at the outlet of the wheel to deviate considerably from the radial direction of the blades. One result of this is a serious mixing and extra turbulence in the outflow from the rotor. This condition causes excessive losses in the diffuser, and the performance of such wheels is difficult to analyze accurately.

In the present wheel an attempt was made to minimizine these difficulties by utilizing two features, namely, a mixed-flow rotor configuration, and a deloaded blade shape. In a mixed flow rotor the flow channels never turn to a completely radial direction; therefore, the flow maintains an appreciable component of velocity in the axial direction during its entire passage through the rotor. With an impeller of this form the blade need not lie in a purely meridional plane (a radial plane passing through the axis of rotation) but may be designed to follow a spiral path along the hub from inlet to outlet. The strength requirement is adequately satisfied in this case, merely by allowing each local section of the blade to lie in an approximately radial direction. The use of a spiral type of flow path introduces a great deal of flexibility into the aerodynamic design, and permits the use of the so-called

deloaded blade. This may be described roughly as a blade which on its pressure side is essentially concave over the first part of its length and essentially convex over the last part.This reversal of curvature tends to reduce the aerodynamic loading near the blade outlet and increase the loading over the central portion of the blade. It is believed that better agreement between theory and experiment can be obtained by means of these aerodynamic features, which is of particular advantage in relation to the research purposes for which this machine is intended. It is also thought that these features should improve the efficiency somewhat, although this consideration is of secondary importance for the present application which is concerned primarily with the suitability of the design for the research task at hand rather than its absolute performance as a compressor.

The impeller was designed by a graphical method which treated the flow as isentropic, compressible and axially symmetric. Details of the method are outlined in reference (1). (See list of references at end of report).

Mechanical Features of Motor Impeller Assembly

The most interesting mechanical features are the method of mounting the impeller, and the method of retracting the motor.

The impeller rotor is mounted directly on the shaft of the driving motor, without any outboard bearing of its own. The motor shaft and its bearings are especially designed not only to take this heavy static load but also to raise the critical speed of the motor-impeller assembly above the operating speed of the motor.

The motor is mounted on a track in such a way that it can easily be retracted to permit access to the interior of the machine. The design and the alignment of the track are such that the impeller can be retracted and reinserted without impairing the close running clearances that must be maintained. The radial clearances between the impeller and the labyrinths are of the order of 0.010 to 0.020 inches. Further details of the track and motor support are shown in Fig. 6.

Measurement of Pressure within the Rotor; The Pressure Transmission System

Central feature of the present installation is the provision of a simple mechanical method for measuring the pressures at various points along the surfaces of the rotating blades by transmitting these pressures via a fluid seal to stationary external manometers. The method of accomplishing this is shown schematically in Fig. 11. The hollow interior of the rotor is divided into eight separate annular air spaces as shown. These are formed by a set of interleaved annular rings. Every second one of these rings is fastened to the rotor and rotates with it. The alternate rings are stationary. Distilled water is admitted under pressure into the spaces between the rings. By reason of its viscosity, the water is set into rotation by the moving impeller, whereupon centrifugal force holds it outward against the inner surface of the rotor. Holes near the outer radii of the rotating rings permit the water to reach a common depth in the annular chambers. The outer circumference of each stationary ring is immersed in the water, so that the latter acts as a seal, effectively separating the eight annular airspaces from one another.

Static pressure taps are provided at various locations on the blade surfaces. By means of pressure lines cast into the impeller, the taps are connected with the annular air chambers. Stationary pressure lines lead from these air chambers to a bank of manometers. The pressures at eight different locations on the blade surfaces can be measured simultaneously. The entire pressure transmission system is arranged within a tapered insert. For simplicity, this insert is not shown in Fig. 11. The insert can be placed within the rotor in four different angular positions which are denoted in Fig. 12 as quadrants I, II, III and IV respectively. In each of these positions a different set of eight pressures can be measured, or thirty-two in all. To change from one quadrant to another, the impeller must be retracted, an operation which is relatively simple because of the design feature of the track previously described.

In designing the rotor it was decided to measure the pressures at five different normals along three different streamlines, on both sides of the blades, as shown in Fig. 12. With 32 pressure taps available, it was possible to make one pair of readings in duplicate. The pair of taps located at the junction of the middle normal with the mean streamline were chosen for this purpose. The various pressure taps are grouped along several different blades as indicated in Table I. Inasmuch as all blades are identical in form, except for manufacturing tolerances, each tap should normally give a result which is valid for all blades at the corresponding location.

The air in the pressure lines within the rotor is subject to a centrifugal force which produces a pressure differential in the radial direction. Consequently, the measured manometer pressure must be corrected for the amount of this difference in order to determine the true pressure at the blade surface. This correction is derived in Appendix II.

In the process of casting the rotor, the thin cores which were used to produce the various pressure lines were inadvertently shifted from their original design positions. As one result of this occurrence the pressure tap locations at the blade surface were shifted to a small extent from their design locations as shown in Fig. 12. Inasmuch as the actual locations are accurately known, however, this produces no serious problem.

The shifting of the cores, however, destroyed the carefully designed alignment between the holes in the rotor and those in the insert. Consequently, it became necessary to redesign the pressure transmission assembly to reestablish contact with the shifted pressure lines in the rotor. This redesign and the associated changes in the impeller caused considerable delay in completing the test rig.

<u>Measurement of Pressures along Stationary Walls and Vanes, and across Stationary Channels</u>

A large number of fixed pressure taps has been provided to obtain a complete picture of the flow conditions in the stationary passages. Locations of the various pressure taps along the stationary walls are shown in Figs. 13 to 16. Since the frames are made of wood, additional taps may easily be placed whereever required. Each pressure tap is designated by a symbol in accordance with the system shown in the foregoing drawings. This system will also be applied to any additional pressure taps which may be added in the future.

In order to permit a detailed determination of the pressure distribution about the diffuser vanes, nine of these 44 vanes have been provided with numerous pressure taps, as shown in Fig. 17. Each vane has 15 pressure taps, the leads of which may be seen in Fig. 5. These taps are arranged in three different patterns denoted in Fig. 17 by the letters A, B, and C. Three blades of each pattern have been provided. The taps are spaced in a regular fashion at 10 chordwise stations on the suction side of the blade and 5 chordwise stations on the pressure side.

Numerous wall taps are also provided in the vicinity of these vanes, so that a very complete picture of the flow may be obtained in this region. Fig. 18 shows the location of these holes with reference to the positions of the diffuser vanes.

Provision has also been made for determining the distribution of pressure, velocity and flow direction across the inlet and diffuser channels at various locations. This is done by means of adjustable probes which can be moved across the channel, and rotated for proper alignment with the direction of flow. These probes are carried by electrically operated actuators which may be seen in Fig. 4.

Special fixtures have been provided upon which the probe actuators may be mounted. These fixtures permit the probe actuator to be moved circumferentially over an arc of approximately 20 degrees, thus making it possible to investigate the variation of flow conditions in the peripheral direction. Four such fixtures have been installed, two at diametrically opposite locations downstream of the inlet guide vanes, and two at diametrically opposite locations downstream of the diffuser vanes. The arcs covered by the probes are shown in Figs. 13 and 15.

In addition, fittings have been provided at fixed locations along the inlet as shown in Fig. 19. A probe actuator may be installed at any of these locations to measure the corresponding flow conditions across the channel at that station. Additional probe actuator fittings may readily be installed at other locations if required.

In studying flow conditions along walls and vanes, it is necessary to know accurately the form of the flow boundaries. The contours of the main flow channel are defined in Fig. 20 and Table IV. The profiles of the inlet and diffuser vanes are given in Fig. 21.

Measurement of Speed and Power

The unit now operates at approximately 1800 rpm and uses on the order of 15 hp. It is driven by a three phase induction motor rated at 40 hp, so that ample power is available for all foreseeable operations in the present speed range.

At some time in the future it is expected to increase the operating speed to approximately 3600 rpm, using another impeller. Since power increases as the cube of speed, this change will increase the power requirement by a factor of eight. The present motor is designed basically to satisfy this higher power need, and can readily be altered to provide 300 H.P. at 3600 rmp.

Operation at the lower speed is necessary for the present because the strength and ductility of the rotor material (cast aluminum) is significantly below specifications. It was considered more economical of time and money to utilize the present rotor at the lower speed than to replace the rotor. Furthermore, it was considered convenient and desirable to obtain some operating experience and do some of the earlier research work at the lower speed. The main advantage of the higher speeds is that all pressures will be increased by a factor of about four so that measurement errors of given absolute magnitude will be reduced in relative amount. This increases in precision will no doubt be valuable in later more refined work, but is not considered necessary for the earlier studies.

Speed measurement will be by means of an ordinary mechanically driven electrical tachometer, or if necessary by an electronic counter.

Accurate evaluation of the compressor efficiency and flow losses depends on obtaining an accurate measurement of net shaft power input. The method chosen as the most practical for the present installation is to establish an accurate calibration between net shaft power and total electrical power input. Then the net shaft power can be determined for any case from measurements of the electrical power input. Since the power supply is three phase, two watt meters with current and voltage transformers are necessary for this purpose.

Preliminary calibration data for the present motor are given in Figs. 22 and 23. These data also show the torque speed relations for this motor. These preliminary calibration curves do not show the effects of possible variations in line voltage or ambient temperature. However, the motor manufacturer will supply quantitative data on these effects, so that an accurate calibration will be available for any normal operating condition.

To obtain the net shaft power input to the impeller, the friction power absorbed by the fluid seals in the pressure transmission system must be deducted from the power delivered at the motor shaft.

Provision has been made to measure the torque reaction between the rotor and the pressure transmission assembly by a weighing scale, as shown in Fig. 4. The corresponding power loss can then be readily computed from the measured torque and rotor speed.

Results of Initial Tests

The overall performance characteristics of the machine are shown in Fig. 24 which is based on data taken during preliminary runs. Data were taken at about 1800 rpm with the inlet guide vanes set in the radial position (zero whirl at impeller inlet) and the diffuser vanes set at an angle of 50 degrees with respect to the radial direction. The curves show pressure coefficient as a function of flow coefficient. These quantities are defined as follows:

Pressure Coefficient $\psi = \dfrac{\Delta p}{\frac{\rho_a}{2} U^2}$

Flow Coefficient $\phi = \dfrac{Q_a}{A_m U}$

where

Δp = Net pressure rise through the compressor as measured in the plenum, lb/ft^2

ρ_a = ambient air density, $slugs/ft^3$

U = peripheral speed of rotor at outlet mean streamline (28.48 in. diam.)

$\frac{\rho_a}{2} U^2$ = reference dynamic pressure corresponding to peripheral speed. 59.345 lb/ft^2 at standard conditions of 520°R and 29.92 in Hg, at 1800 rpm.

Q_a = volumetric flow rate referred to ambient conditions, ft^3/sec.

A_m = area of flow annulus at rotor outlet, 1.726 ft^2

$A_m U$ = reference volumetric flow rate, 386.2 ft^3/sec at 1800 rpm.

From these results it may be seen that at 1800 rpm the pressure rise in the plenum never exceeds about 71 lb/ft^2. Even if the compression takes place at an overall adiabatic efficiency of only 70%, the change in air density in passing through the machine is still less than two percent. Therefore, at 1800 rpm changes in density can be neglected. At 3600 rmp, however, these changes will have to be taken into account.

Fig. 24 shows that the flow rate through the machine at 1800 rpm varies from about 73 ft^3/sec at surge to an upper limit that depends on the flow resistance in the discharge line when the throttle valve is wide open. The preliminary results of Fig. 24 were obtained using a throttle valve of relatively high flow resistance so that the maximum flow obtainable was only about 106 ft^3/sec with the $11\frac{1}{2}$ in. diameter orifice, or about 130 ft^3/sec with the $13\frac{1}{2}$ in. diameter orifice. The original throttle valve is being replaced by another type, shown in Fig. 2, which has a very low friction loss. This will permit future operation over a substantially broader range of flow rates.

An efficiency curve corresponding to the above range of operating conditions could not be obtained during the preliminary runs inasmuch as the necessary electrical instruments were not available.

From Fig. 24, the power requirements were estimated to range from 11 to about 20 hp.

The distribution of the dimensionless pressure coefficient ψ along the stationary walls is summarized in Fig. 25.

The pressure coefficients along the impeller blades were determined for quadrant I (refer to Fig. 12). Results are summarized in Table V.

Research Possibilities

The present experimental facility has a wide range of usefulness both for pedagogical and research purposes. It will stimulate the interest of students at the U. S. Naval Postgraduate School in the important field of turbomachinery. It will suggest useful research problems and provide the means for their investigation. Some of these possibilities are discussed below.

1. Evaluation of current simplified design theory

As pointed out earlier, the present impeller was designed on the basis of a simplifier analysis, typical of current design practice. This theory neglects the viscosity of the air and the variation of flow conditions from point to point in the peripheral direction. Therefore, the three dimensional flow of a viscous fluid is replaced by a two-dimensional flow of a non-viscous fluid. It is important to know how seriously these simplifications affect the final result.

2. Evaluation of blade loading distribution

A second aspect of the present design relates to the effect of the deloaded blade design previously explained. It is of interest to check whether the loading varies in the manner predicted, and to what degree slip and mixing effects at the blade outlet are influenced.

3. Blade interference effects

A large proportion of the total losses of the compressor is produced in the diffuser not so much because of its inherent characteristics as because of the non-uniform flow conditions produced by the blades at the rotor exit. A proper choice of the inlet angle of the diffuser vanes can nevertheless minimize these losses. A similar condition prevails at the impeller inlet. Because of the possibility of changing the angular position of both inlet and diffuser vanes, a thorough investigation of this blade interference problem can be undertaken.

4. Correlation of internal flow effects with overall operating characteristics

The operation of a compressor is normally evaluated in terms of overall operating characteristics, namely, the pressure coefficient, the flow coefficient, and the efficiency, since they can be determined easily. The correlation between these overall characteristics and the details of the corresponding internal flow is not sufficiently well understood. This is especially true at two operating conditions of basic significance, namely, operation at maximum efficiency, and operation at surge. In regard to the first of these, it is of great importance to know just what combination of

detailed flow characteristics produces maximum efficiency. In regard to the second, it is important to know exactly why the flow breaks down and gives rise to the phenomenon of surge.

5. Investigation of secondary flow in rotating channels

Even if viscosity effects be neglected, the flow in a rotating channel differs significantly from that obtained under the assumption of polar symmetry, in that this assumption violates the actual nature of the vorticity in the channel. Actually there exists a secondary motion, which should be added to the simplified flow to establish the true conditions. Hence the secondary flow is in the nature of a correction which gives a closer approximation to the actual flow pattern existing in the machine. The theoretical determination of this secondary flow is quite complex, but can be handled by digital computers such as the one at the U. S. Naval Postgraduate School (see Appendix III). It would be of great value to check the degree of improvement in the prediction of performance obtained in this manner.

6. Investigation of boundary layer effects

Drag, energy loss, and flow separation are due to boundary layer phenomena. Very little is known of boundary layer behavior under the complex conditions prevailing in turbo-machinery.

7. Investigation of high frequency pulsations

As a result of the relative motion between stationary and rotating blades, the flow within a turbo-machine fluctuates at high frequency. Little is known concerning the magnitude and distribution of these fluctuations, of their effects on flow processes and overall performance characteristics. For studying these problems the present facility can be equipped with dynamic pressure measuring and recording devices.

8. Correlation of geometrical design variables

Within given limitations of space, a large number of significant variations in the shape of rotor and blades is possible. It would be of great value to study, in a systematic manner, the influence of such variations both theoretically and experimentally. The only additional requirement would be to construct a series of wheels which embody these systematic variations in form. It is believed that the knowledge gained from such a program would be well worth the cost involved.

While by no means exhaustive, the foregoing list should suffice to indicate the research potentialities of the test facility described in this report.

References

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(2) "Fluid Meters", ASME Research Publication, Fourth Edition, 1937.

(3) "Standards for Discharge Measurement with Standardized Nozzles and Orifices, German Industrial Standard DIN 1952", N. A. C. A. Technical Memorandum No. 952, Sept. 1940.

List of Symbols

A	-	area	ft^2
A_1	-	cross section area of discharge pipe	ft^2
A_2	-	cross section area of orifice	ft^2
A_m	-	area of impeller exit annulus	ft^2
b	-	barometer	in. Hg
C	-	theoretical discharge coefficient	---
c	-	constant (see App. III)	
D_1	-	diameter of discharge pipe	in.
D_2	-	diameter of orifice	in.
d	-	constant (see App. III)	
E	-	see Eq. 3.2	
e	-	constant (see App. III)	
F	-	see Eq. 3.3	
f	-	constant (see App. III)	
G	-	see Eq. 3.4	
g	-	acceleration of gravity	ft/sec^2
H	-	see Eq. 3.5	
h	-	height of fluid column corresponding to pressure p, measured with manometer	in., or cm.
h_a	-	height of fluid column corresponding to atmospheric pressure, measured with manometer	in., or cm.
I	-	see Eq. 3.6	
i	-	constant (see App. III)	
J	-	see Eq. 3.7	
K	-	experimental flow coefficient	
L, L_B, L_M	-	see Eq. 3.11a or 3.11b	
l	-	constant (see App. III)	
M	-	see Eq. 3.13	
m	-	constant (see App. III)	
N	-	impeller speed	rpm
N	-	reference impeller speed = 1800	rpm
n	-	constant (see App. III)	

O	-	see Eq. 3.14	
P	-	absolute pressure	
P_a	-	atmospheric absolute pressure	
p	-	gage pressure	
p'	-	height of water column, corresponding to p, measured with micro-manometer	cm.
p′	-	measured rotor pressure, before correcting for centrifugal effect	lb/ft^2
Δp	-	pressure difference across orifice	
$\Delta p'$	-	height of water column, corresponding to Δp, measured with micro-manometer	cm.
Q	-	volumetric flow rate	ft^3/sec
Q_a	-	volumetric flow rate referred to prevailing atmospheric conditions	ft^3/sec
Q_o	-	constant (see Eq. 1.11 and Table VI)	ft^3/sec
q	-	constant (see App. III)	
R	-	gas constant	$ft/^oR$
R	-	code for pressure taps of impeller blades (see Table IX)	
R	-	radius of pressure taps of impeller blades	in.
R_o	-	radius of impeller at outlet mean streamline	in.
R_i	-	inner radius of pressure transmission system	in.
S	-	code for manometer fluid and dimension of measured fluid column (see App. III)	
T	-	absolute temperature	^oR
t	-	temperature	^oF
U	-	peripheral speed of impeller at outlet mean streamline at N rpm	ft/sec
U_o	-	peripheral speed of impeller at outlet mean streamline at 1800 rpm	ft/sec
V	-	velocity	
W	-	see Eq. 3.15	
w	-	conversion factor (see App. III)	
X	-	number of flow rate to be processed	
Y	-	number of pressure to be processed	
Y_1	-	compressibility factor (see Eq. 1.7)	
Z	-	code for type of manometer used for measurement (see App. III)	
$\gamma = \frac{C_p}{C_v}$	-	ratio of specific heats	
ε	-	see Eq. 1.8	
ξ	-	see Eq. 3.16	
ρ	-	mass density	$slugs/ft^3$
ϕ	-	flow coefficient (see Eq. 1.13)	---
ϕ_o	-	constant (see Eq. 1.16 and Table VI)	---
ψ_1	-	pressure coefficient (see Eq. 2.1)	---
ψ	-	pressure coefficient (see Eq. 2.7)	---
$\Delta\psi$	-	correction factor for ψ for centrifugal effect (see Eq. 2.8)	
ω	-	angular velocity of impeller	rad/sec

Subscripts

a refers to ambient conditions
o " " standard reference conditions
1 " " station upstream of orifice
2 " " station at orifice
c " " vena contracta of flow through orifice
i " " ideal, frictionless conditions

Appendix I <u>Derivation of Basic Equation for Flow Coefficient</u>

The set up for determining the flow rate is shown in Fig. 2. A square edged orifice is set into the discharge pipe. The pressure drop Δp across the orifice is measured with a micromanometer. The flow rate in terms of the dimensionless flow coefficient ϕ may then be obtained from Eq. (1.15).

The symbols used are defined on page 13.

The following relationships are used in deriving the basic flow equation.

$$P_1 + \frac{\rho_1}{2} V_1^2 = P_c + \frac{\rho_1}{2} V_{c_2}^2 \tag{1.1}$$

$$Q_1 = A_1 V_1 = A_2 V_2 = A_c V_c \tag{1.2}$$

$$C = \frac{V_c}{V_{c_2}} \cdot \frac{A_c}{A_2} \tag{1.3}$$

Eq. (1.1) is Bernoulli's equation for frictionless flow between station ① upstream of the orifice and station © at the vena-contracta of the jet. Eq. (1.2) is the continuity equation for incompressible flow. Eq. (1.3) defines the theoretical discharge coefficient C.

From these equations the volumetric flow rate referred to conditions ahead of the nozzle is

$$Q_1 = \frac{C}{\sqrt{1 - C^2\left(\frac{A_2}{A_1}\right)^2}} A_2 \sqrt{\frac{2}{\rho_1}(P_1 - P_c)} \tag{1.4}$$

Replacing the pressure different (P_1-P_c) by the measured pressure drop Δp across the orifice, and replacing the quantity $\frac{C}{\sqrt{1 - C^2\left(\frac{A_2}{A_1}\right)^2}}$ by the experimentally determined flow coefficient K,

$$Q_1 = K A_2 \sqrt{\frac{2}{\rho_1} \Delta p} \tag{1.5}$$

For application to a compressible fluid the foregoing relation is modified by the introduction of an empirically determined compressibility factor Y_1 whereupon

$$Q_1 = K Y_1 A_2 \sqrt{\frac{2}{\rho_1} \Delta p} \tag{1.6}$$

According to reference (2), page 66, the compressibility correction is governed by the empirical relation

$$Y_1 = 1 - \varepsilon \frac{\Delta p}{P_1} \tag{1.7}$$

where $$\varepsilon = \frac{1}{\gamma}\left[0.41 + 0.35\left(\frac{A_2}{A_1}\right)^2\right] \qquad (1.8)$$

The value of the flow coefficient K depends on three variables

(1) The area ratio $\frac{A_2}{A_1}$.

(2) The location of the pressure taps.

(3) The Reynold's number of the flow.

Three different orifices are available, with diameters of $11\frac{1}{2}$, $13\frac{1}{2}$, and $15\frac{1}{2}$ in., respectively. The inside diameter of the pipe is $23\frac{1}{4}$ in.

A reliable measurement of the average pressure difference across the orifice is obtained by connecting upstream and downstream taps to separate manifolds as shown in Fig. 2. This average pressure difference Δp, and the upstream pressure p_1, are measured by a micromanometer.

The location of the taps corresponds to German practice as described in reference (3). This reference was, therefore, used in determining the flow coefficient K of Table VI. Values taken from the nearest equivalent in American practice,as covered in reference (2), give substantially the same results.

The Reynold's number, based on orificed diameter, ranges from about 450,000 to 900,000. For these Reynold's numbers, the variation in the flow coefficient K is negligible. Hence the values given in Table VI for the several orifices may be regarded as constants.

The air density ρ_1 upstream of the orifice may be written in terms of the perfect gas law

$$\rho_1 = \frac{P_1}{gRT_1} \qquad (1.9)$$

Using this substitution, Eq. (1.6) becomes

$$Q_1 = Q_0 Y_1 \sqrt{\frac{T_1}{T_0}} \sqrt{\frac{\Delta p}{P_1}} \qquad (1.10)$$

where $$Q_0 = K A_2 \sqrt{2gRT_0} \qquad (1.11)$$

The quantity Q_0 is a constant which depends only on the size of the orifice being used. See Table VI.

Eq. (1.10) gives the volumetric flow rate in terms of the density upstream of the orifice. It is desirable to refer the volumetric flow rate to conditions at the compressor inlet. This is accomplished through the relation

$$Q_a = \frac{\rho_1}{\rho_a} Q_1 = \frac{P_1}{P_a} \cdot \frac{T_a}{T_1} Q_1 \qquad (1.12)$$

The dimensionless flow coefficient ϕ is defined by

$$\phi = \frac{Q_a}{A_m \mathcal{U}} \tag{1.13}$$

where A_m is the area of the rotor outlet flow annulus and $\mathcal{U}$ is the peripheral speed of the impeller at the outlet mean streamline. If $\mathcal{U}_0$ is the peripheral speed at $N_0 = 1800$ rpm, the corresponding value at any other rpm N is

$$\mathcal{U} = \mathcal{U}_0 \left(\frac{N}{N_0}\right) \tag{1.14}$$

By combining Eqs. (1.10), (1.12), (1.13), and (1.14)

$$\phi = \phi_0 \, Y_1 \left(\frac{N_0}{N}\right)\left(\frac{T_a}{T_1}\right)\sqrt{\frac{T_1}{T_0}} \left(\frac{P_1}{P_a}\right)\sqrt{\frac{\Delta p}{P_1}} \tag{1.15}$$

where $$\phi_0 = \frac{Q_0}{A_m \mathcal{U}_0} \tag{1.16}$$

The quantity ϕ_0 is a constant that depends only on the diameter of the orifice used. See Table VI.

Appendix II Calculation of Pressure Coefficients

It is of advantage to express all gage pressures throughout the compressor in terms of the dimensionless pressure coefficient which is defined by the expression

$$\psi = \frac{p}{\frac{\rho_a}{2} U^2} \qquad (2.1)$$

where

p = actual gage pressure, lb/ft^2

ρ_a = density of ambient air, $slugs/ft^3$

U = peripheral speed of impeller measured at outlet mean streamline, ft/sec

$\frac{\rho_a}{2} U^2$ = dynamic reference pressure, lb/ft^2

The actual density ρ_a and the actual peripheral speed U may be expressed in terms of the reference values ρ_o and U_o corresponding to standard conditions P_o, To and N_o.

Thus:

$$\rho_a = \frac{P_a}{P_o} \frac{T_o}{T_a} \rho_o \qquad (2.2)$$

$$U = \frac{N}{N_o} U_o \qquad (2.3)$$

With these substitutions, Eq. (2.1) becomes

$$\psi = \left(\frac{N_o}{N}\right)^2 \left(\frac{T_a}{T_o}\right) \left(\frac{P_o}{P_a}\right) \cdot \frac{p}{\frac{\rho_o}{2} U_o^2} \qquad (2.4)$$

The following reference values have been chosen .

P_o = 2116 lb/ft^2 = 14.7 $lb/in.^2$ = 29.92 in. Hg.

T_o = 520 °R

ρ_o = 0.0023709 $slugs/ft^3$

N_o = 1800 rpm

$\frac{\rho_o}{2} U_o^2$ = 59.345 lb/ft^2

By reference to Fig. 11, it may be seen that in determining the pressure at any point along the rotor blade, the corresponding manometer reading must be corrected for the effect of centrifugal force acting on the air in the rotating pressure line within the impeller. The centrifugal force acting on an element of the fluid is balanced by a radial pressure gradient. Thus from considerations of equilibrium

$$p = p' + \frac{\rho\omega^2}{2}\left[R^2 - R_i^2\right] \qquad (2.5)$$

where p' = gage pressure measured at manometer, lb/ft^2
p = true gage pressure at blade tap, lb/ft^2
ρ = density of air in tube, slug/ft^3
ω = angular velocity of impeller, rad/sec.

The corresponding pressure coefficient ψ as defined by Eq. (2.1) becomes

$$\psi = \frac{p}{\frac{\rho_a}{2}U^2} = \frac{p'}{\frac{\rho_a}{2}U^2} + \left(\frac{\rho}{\rho_a}\right)\left(\frac{R^2 - R_i^2}{R_o^2}\right) \qquad (2.6)$$

Since compressibility effects are negligible (at 1800 rpm), it is permissible to assume $\rho/\rho_a = 1.$
Then introducing the notation

$$\psi' = \frac{p'}{\frac{\rho_a}{2}U^2} = \left(\frac{N_o}{N}\right)\left(\frac{T_a}{T_o}\right)\left(\frac{P_o}{P_a}\right)\frac{p'}{\frac{\rho_o}{2}U_o^2} \qquad (2.7)$$

$$\Delta\psi = \frac{R^2 - R_i^2}{R_o^2} \qquad (2.8)$$

The final pressure coefficient may be written simply as

$$\psi = \psi' + \Delta\psi \qquad (2.9)$$

Numerical values of $\Delta\psi$ for the various blade taps are listed in Table VII.

APPENDIX III - DATA REDUCTION WITH DIGITAL COMPUTER

The Computation Center of the Department of Mathematics and Mechanics of the United States Naval Postgraduate School is equipped with a General Purpose Computer CRC 102-A (built by the Electronics Division of the National Cash Register Company, Hawthorne, California). This is an electronic, magnetic drum type, serial computer with a word length of 42 binary digits. It operates with a three-address code and the main memory on the magnetic drum can store 1024 words. A Magnetic Tape Unit Model CRC 126 provides additional storage for about 130,000 words, which, controlled by the program, can be transferred to and from the main memory in 8 word sequences. The input to and the output from the computer are either by automatic typewriter (Flexowriter) or IBM card machines. The Flexowriter can punch or read paper tapes for numerical data and commands. A Digital Point Plotter CCP 701 (built by California Computer Products, Los Angeles, Calif.) is controlled and operated by the computer for data output in graphical form.

The computer permits rapid reduction of test data, and thereby increases the usefulness of the Compressor Test Rig by a large factor. For instance, the values of Table V were calculated and the table typed in about 40 minutes. Simultaneously, they were automatically plotted in a manner similar to that shown in Fig. 24. Fig. 26 shows the installation of the Computer. On its left is the magnetic tape unit. The operator's console with the Flexowriter is in the foreground. The digital plotter is on the right, in front of the IBM machines for reading and punching cards.

The authors wish to thank Prof. Randolph W. Church, Chairman of the Dept. of Mathematics and Mechanics of the United States Naval Postgraduate School, for his foresight and efforts, and the Bureau of Ships, United States Navy, for its support in establishing the computing facility. Prof. C. L. Perry in charge of the Computation Center, was extremely helpful in giving advice and suggestions in connection with the coding. Prior to this, Prof. Perry spent a considerable part of his time, besides his many regular duties, in instructing the authors in the principles of coding and in the operation of the computer. With this instruction and the help of Prof. Perry, the senior author was able to code and check the entire program in about two weeks. Thanks to the efforts and the professional skill of Mr. Norman Bernstein, the Computer is kept in such good operating condition, that the scheduling of computation work does not present any difficulties.

Modification of Equations of Flow and Pressure Coefficients for Calculation with Computer.

a) Flow Coefficients.

The flow coefficient ϕ is determined by (see Eq. (1.15))

$$\phi = \phi_0 \left[1 - \varepsilon \frac{\Delta p}{P_1}\right] \frac{N_0}{N} \frac{P_1}{P_a} \frac{T_a}{T_1} \sqrt{\frac{T_1}{T_0}} \sqrt{\frac{\Delta p}{P_1}}$$

For a given orifice diameter, ε and ϕ_o are constants. The barometer b is measured in inches of mercury. The values $\Delta p'$ and p_1' are measured in cm. of water. The latter two values must be corrected by the zero pressure reading Δ of the micromanometer, since $\Delta p = \Delta p' - \Delta$, and $p_1 = p_1' - \Delta$. With $P_a = b(34.417)$ in cm. of water, $T_1 = t_1 + 459.4$ °R, $T_a = t_a + 459.4$ °R

$$\frac{P_1}{P_a} = 1 + \frac{p_1}{b(34.417)}$$

$$\frac{\Delta p}{P_1} = \frac{\Delta p}{b(34.417) + p}$$

For processing with the computer, the expression for ϕ must be rearranged so that all factors become smaller than unity. With $T_0 = 520$ °R, $N_0 = 1800$ RPM,

$$\left(\frac{\phi}{10}\right) = 2^5 \left(\frac{\phi_o}{10}\right) EFGH\sqrt{IJ} \tag{3.1}$$

where

$$E = \frac{1}{2} - \left(\frac{\varepsilon}{2}\right) I \tag{3.2}$$

$$F = \frac{1}{2} + \frac{\frac{1}{2}\left(\frac{p_1}{100}\right) c}{\left(\frac{b}{100}\right)} \tag{3.3}$$

$$G = \frac{\frac{1}{4} + \left(\frac{t_a}{100}\right) d}{\frac{1}{2} + \left(\frac{t_1}{100}\right) e} \tag{3.4}$$

$$H = \frac{i}{(N/10^4)} \tag{3.5}$$

$$I = \frac{\left(\frac{\Delta p}{100}\right) c}{\left(\frac{b}{100}\right) + \left(\frac{p_1}{100}\right) c} \tag{3.6}$$

$$J = f + \left(\frac{t_1}{100}\right) g \tag{3.7}$$

The constants in these equations are:

$$c = \frac{1}{34.417} = 0.0290554$$

$$d = \frac{1}{4}\,\frac{100}{459.4} = 0.0544188$$

$$e = \frac{1}{2}\,\frac{100}{459.4} = 0.1088376$$

$$f = \frac{1}{4}\,\frac{459.4}{520} = 0.2208653$$

$$q = \frac{1}{4}\,\frac{100}{520} = 0.0480769$$

$$i = \frac{1800}{2\times 10^4} = 0.0900000$$

The values of ε and ϕ_o are given in Table VI.

b) Pressure Coefficients

The pressures are measured by two different types of manometers. If measured on a manometer board (Fig. 27a), the gage pressure p in lb/ft^2 is

$$p = (h_a - h)w \qquad [lb/ft^2] \tag{3.8a}$$

If measured with a micro-manometer the pressure is

$$p = (h - h_a)w \qquad [lb/ft^2] \tag{3.8b}$$

The conversion factor w is:

$w = 5.198$ if h, h_a are measured in inches of water
$w = 4.2104$ if h, h_a are measured in inches of alcohol
$w = 2.0465$ if h, h_a are measured in cm. of water
$w = 1.6576$ if h, h_a are measured in cm. of alcohol

The alcohol used in the manometers has a gravity of 0.81 at room temperature.

The pressure coefficient ψ is determined (see Eqs. 2.7 and 2.9) by

$$\psi = \left(\frac{N_o}{N}\right)^2\left(\frac{T_a}{T_o}\right)\left(\frac{P_o}{P_a}\right)\frac{p}{\frac{\rho_o}{2}U_o^2} + \Delta\psi \tag{3.9}$$

At N_o = 1800 RPM, b_o = 29.92 in. Hg, T_o = 520°R, P_o = 2116 lb/ft^2 = 29.92 in. Hg, $\frac{\rho_o}{2}U_o^2 = 59.3453\ lb/ft^2$,

$$\psi = p\left(\frac{29.92}{b}\right)\left(\frac{T_a}{520}\right)\left(\frac{1800}{N}\right)^2(0.01685053) + \Delta\psi \tag{3.10}$$

Where $\Delta\psi = \frac{R^2 - R_i^2}{R_o^2}$ for the pressure taps of the impeller blades. For the pressure taps on the stationary walls $\Delta\psi$ is zero.

Let

$$L = L_B = \left(\frac{h_a}{100} - \frac{h}{100}\right) \tag{3.11a}$$

$$L = L_M = \left(\frac{h}{100} - \frac{h_a}{100}\right) \tag{3.11b}$$

L_B must be used for measurements with a bank of manometer tubes, and L_M for

measurements with a micro-manometer. For processing with the digital computer, all factors of Eq.(3.10) must be made smaller than unity, hence

$$\left(\frac{\psi}{10}\right) = 2^4 LMOW\xi + \left(\frac{\Delta\psi}{10}\right) \tag{3.12}$$

where L is either L_B or L_M (Eq. 3.11a or 3.11b), and

$$M = \frac{\ell}{\left(\frac{b}{100}\right)} \tag{3.13}$$

$$O = m + \left(\frac{t_a}{100}\right)n \tag{3.14}$$

$$W = \left[\frac{i}{(N/10^4)}\right]^2 \tag{3.15}$$

$$\xi = 0.1685053w \tag{3.16}$$

The constants of these equations are:

$$i = \frac{1800}{2x10^4} = 0.0900$$

$$l = \frac{1}{2}\ \frac{29.92}{100} = 0.1496$$

$$m = \frac{1}{2}\ \frac{459.4}{520} = 0.4417307$$

$$n = \frac{1}{2}\ \frac{100}{520} = 0.0961538$$

The values of ξ are given in the following tabulation. They depend on the units in which the fluid columns are measured and the type of fluid used in the manometers.

h, h_a measured in:	Inches Water	Inches Alcohol Gravity 0.81	Cm. Water	Cm. Alcohol Gravity 0.81
ξ =	0.8758906	0.7094714	0.3448461	0.2793253

Description of Computing Program.

The complete coding of the program is given in Appendix IV. The program contains all the operations necessary for the calculation of the values of ϕ and ψ, for measurements with different orifice diameters, for different types of manometers, different kinds of manometer fluids, and different dimensions of the fluid columns. The same program is used for the reduction of pressures measured both on the rotor blades and on the stationary walls or vanes. The program is coded in such a way that the computer can distinguish between 48 different types of measuring combinations. This differentiation is controlled solely by the data input, without requiring changes of the program by the operator. After each run the program is automatically restored to its original form, to make possible any number of subsequent runs without requiring changes of the memory contents by the operator. If the program is interrupted either by a computer error or by wrong manipulations, it can be restored by special commands to re-start the computations.

The calculated values of ϕ and ψ are stored on a magnetic tape, in a manner which permits the typing of a final table of results without a human operator. This table has the form shown in Table VIII. The heading of the table and the appropriate column headings Y = 1, 2, 3 -----Ymax are printed automatically by the program for all values of Ymax between 1 and 15. The table heading is automatically centered irrespective of the number of columns required in the table, and the necessary carriage returns and other operations of the Flexowriter are completely controlled by the program.

With a single run the program can process 15 values of ψ for each of 64 values of ϕ, hence the largest values of Xmax and Ymax are 64 and 15, respectively. Thus 960 values of ψ may be calculated per run. However, any combination of Xmax and Ymax, can be processed, provided the same number of ψ's (or Ymax) occurs for all values of ϕ (or X). While typing the table the Flexowriter can punch a paper tape. Once such tapes are available the corresponding tables can be duplicated directly for reproduction by Mimeograph or Multilith methods. If such reproductions are made on 8 by 10 1/2 in. paper the values of Xmax and Ymax should not exceed 34 and 11, respectively.

The measured data are typed and punched on so-called Data Tapes (see: Instructions for Preparation of Data Tapes). These data tapes are read into the computer by the Flexowriter. After the reading of the first sets of data, necessary for the determination of ϕ_1 or $\psi_{1,1}$ the reading of the subsequent data is controlled by the program, and the computer stops automatically after the last set of data has been processed. Since the measured data are punched on paper tapes, control runs or a duplication of the calculations for other purposes can be carried out without re-typing the measured data. The whole program exclusive of the data tapes is punched on IBM cards, which can be read into the memory of the computer in about 4 1/2 minutes. Prior to computation a memory sum checks the filling process. By positioning the test switches on the control panel of the computer, three pre-selected values of ψ can be plotted during computation for all values of ϕ. This is done by the Digital Plotter, which in turn is operated by the computer and controlled by the program. The graph paper is 15 in. by 10 in. As shown in Fig. 28 the values of ϕ are plotted with a scale of 0.04 per inch, and the values of ψ with a scale of 0.2 per inch. The origin of the diagram ψ vs. ϕ is at x = 0, y = 3 inches. The selected values of ψ_I are plotted with the symbol o, and plotting can be suppressed by moving Test Switch 2020 to the "Up" position. The values of ψ_{II} are plotted with symbol •, and plotting is suppressed if Test Switch 2040 is in

the "Up" position. The values of ψ_{III} are plotted with the symbol +. Plotting is suppressed if the Test Switch 2100 is in the "Up" position. To avoid ambiguity in the results, the number of plotted points has been limited to three per value of ϕ, since the plotter has only three different plotting symbols. If more than three values of ψ have to be plotted, the new values of Y_I, Y_{II}, Y_{III} must be introduced on the Data Tape for ψ, and the program re-run, starting with step 10 of the Operating Instructions. For this additional plotting the tape unit is not required, and can be by-passed with the command/566f/s. By setting up /570f/s, the program is restored for operation with the tape unit. The Test Switch 2010 controls the typing of the values of ψ immediately after computation for checking purposes. If the Test Switch 2010 is in the "Up" position this intermediate printing is suppressed without influencing the storage in the magnetic tape unit. Table IX gives a summary of the contents of the main memory. The listed commands print the respective parts of the memory in octal code with address for checking purposes.

Instructions for Preparation of Data Tapes

1. Punch Data Tape for ϕ with Flexowriter
   a) First set of data (ϕ_1)

		Remarks
o//1100/d(Δp')	Tab	contents to cell 1100
(p_1')	Tab	" " " 1101
(t_1)	Tab	" " " 1102
(t_a)	Tab	" " " 1103
(Δ)	Tab	" " " 1104
(b)	Tab	" " " 1105
(N)	Tab	" " " 1106
0/111/ Xmax	Tab	(octal number of sets of data for ϕ)
s		Starts computation
Space Bar		
Space Bar		
Stop Code		Stops reading from tape

   b) Remaining Sets of Data

		Remarks
Carriage Return		types data on next line
d(Δp')	Tab	contents to cell 1100
(p_1')	Tab	" " " 1101
(t_1)	Tab	" " " 1102
(t_a)	Tab	" " " 1103
(Δ)	Tab	" " " 1104
(b)	Tab	" " " 1105
(N)	Tab	" " " 1106
s		starts computation
Space Bar		
Space Bar		
Stop Code		stops reading from tape

c) Example for typing data

Measured Value	Typing
$(\Delta p') = 17.49$ cm H_2O	1749
$(p_1') = 18.20$ cm H_2O	1820
$(t_1) = 75.2°$ F	7520
$(t_a) = 71°$ F	7100
$(\Delta) = 0.323$ cm H_2O	32
(N) = 1784 RPM	1784

Xmax = octal number of sets of data to be processed per run (e.g. for 17 sets of data per run, type X as 21). The maximum number of sets of data which can be processed per run is 64 or Xmax = 100. If data (t_1) to (N) are the same for all sets, they must be typed for the first set only. If only some of these values change they must be typed with their respective cell number; e.g. a change of Δ must be typed o/1104/d(Δ), if the values (t_1) and t_a do not change.

d) Label Tape as: Data Tape for ϕ; Run number, Orifice diameter, Date of measurements.

2. Punch Data Tape for ψ with Flexowriter. These values must be typed in the sequence $\psi_{1,1}$, $\psi_{1,2}$ ---ψ_1,Ymax; $\psi_{2,1}$, $\psi_{2,2}$ ---ψ_2,Ymax ----ψXmax, Ymax, of Table VIII.

a) First set of data for ψ ($\psi_{1,1}$).

		Remarks
o//1500/Ymax	Tab	Max. number of Y in octal; type Ymax
Y_I	Tab	No. Y for first plot in octal, type: $Y_I$ff
Y_{II}	Tab	No. Y for second plot in octal, type: Y_{II}ff
Y_{III}	Tab	No. Y for third plot in octal type: Y_{III}ff
Stop Code		stops reading after typing contents of cells 1500 to 1503 to permit resetting of Y_I, Y_{II}, and Y_{III} if desired
/Code S/ (No Tab)		Code S = 200 for inches of water Code S = 210 for inches of alcohol Code S = 220 for cm. of water Code S = 230 for cm. of alcohol.
(Code Z)	Tab	Code Z = 1 for Manometer Board Code Z = 2 for Micro-manometer
(Code R)	Tab	for stationary pressure taps: code R = f for rotor blades: code R according to Table X
d(h)	Tab	contents to cell S + 2
(h_a)	Tab	" " " S + 3
(t_a)	Tab	" " " S + 4
(b)	Tab	" " " S + 5
(N)	Tab	" " " S + 6
o/400f/s		starts computation
Space Bar		
Space Bar		
Stop Code		stops reading from tape

b) Remaining sets of data for ψ

		Remarks
Carriage Return		types data on next line
/Code S/ (No Tab)		Code S = 200 for inches of water Code S = 210 for inches of alcohol Code S = 220 for cm. of water Code S = 230 for cm. of alcohol.
(Code Z)	Tab	Code Z = 1 for Manometer Board Code Z = 2 for Micro-manometer
(Code R)	Tab	for stationary pressure taps: code R = f for rotor blades: code R according to Table IX
d(h)	Tab	contents to cell S + 2
(h_a)	Tab	" " " S + 3
(t_a)	Tab	" " " S + 4
(b)	Tab	" " " S + 5
(N)	Tab	" " " S + 6
o/400f/s		starts computation
Space Bar		
Space Bar		
Stop Code		stops reading from tape

c) Example for typing first set of data for ψ

Typing		Remarks	
o//1500/16	Tab	Ymax = 16(Octal) = 14(Dec.)	
2ff	Tab	Y_I = 2(Octal) = 2(Dec.)	Plots Y_I as o
4ff	Tab	Y_{II} = 4(Octal) = 4(Dec.)	Plots Y_{II} as •
12ff	Tab	Y_{III} = 12(Octal) = 10(Dec.)	Plots Y_{III} as +
Stop Code		Stops reading to permit re-setting of Y_I, Y_{II}, Y_{III} if desired.	
/210/ (No Tab)		S = 210: h, h_a measured in inches of alcohol	
2	Tab	Z = 2: h, h_a measured with micro-manometer	
12f	Tab	R = 12f: measured on rotor blades; quadrant 1, measuring line 2 (see table X)	
d1440	Tab	h = 14.40 in. of alcohol	
32	Tab	h_a = 0.32 in. of alcohol	
7150	Tab	t_a = 71.5° F	
3005	Tab	b = 30.05 in. Hg	
1790	Tab	N = 1790 RPM	
o/400f/s			
Space Bar		Starts computation at cell 0400	
Space Bar			
Stop Code		Stops reading from tape	

d) Example for typing of remaining sets of data for ψ

Carriage return		Types data on next line
/220/ (No Tab)		S = 220: h, h_a measured in cm. of water
1	Tab	z = 1: h, h_a measured with manometer board
f	Tab	Stationary pressure tap
d 782	Tab	h = 7.82 cm. of water
2115	Tab	h_a = 21.15 cm. of water
7300	Tab	t_a = 73° F

2900 Tab		$b = 29.00$ in. Hg
1795 Tab		$N = 1795$ RPM
o/400f/s		starst computations at cell 0400
Space Bar		
Space Bar		
Stop Code		Stops reading from tape.

The codes S, Z, and R must be typed for all sets of data. However, if S is equal for a number of subsequent data, and if t_a, b, N are equal also, the values of t_a, b, and N must be typed only for the first set of data with the same code S.

e) Label Tape as: Data Tape for ψ, Run number, Orifice diameter, Date of measurements.

Operating Instructions

1. Clear Memory with Subroutine #100. After print-out, clear input register.

2. Fill Memory from IBM Cards. Insert cards into hopper of IBM Card Reader. Press "Start" button of IBM machine. Read Subroutine #101 into computer with Flexowriter. Press "Compute" button on control panel.

3. Memory Sum Check. After last IBM Card has been read, press "Clear" button, then set up command /750f/s on Flexowriter. Correct filling gives the print-out: 2007 00414032453457. This memory sum check can be carried out after the initial filling only.

4. Read Auxiliary Tape into Computer with Flexowriter
   a) for data with 11.5 in. Dia. orifice: Auxiliary Tape #1
   b) for data with 13.5 in. Dia. orifice: Auxiliary Tape #2
   c) for data with 15.5 in. Dia. orifice: Auxiliary Tape #3

5. Insert Data Tape for ϕ into Reader of Flexowriter and press "Start Read" lever. Computer starts automatically, reads subsequent sets of data from tape, and stops after computation of last set of data for ϕ, namely, ϕ_{Xmax}.

6. Results of $\phi/10$ in octals are stored in channel 12. To type out these results, or to punch a paper tape, set up /353f/s.

7. Results of ϕ in decimal are stored in channel 14. If in addition to $\phi/10$ in octal, the values of ϕ in decimal are to be typed out or punched on a tape also, press "Compute" button on control panel after operation 6 has been completed. To type out, or punch a tape for ϕ in decimal only, set up /355f/s.

   (Steps 6 and 7 are checks only, and can be omitted without influencing the succeeding operations)

8. Attach Graph Paper 10 in. by 15 in. to drum of Digital Plotter. After warm up, set switch to "Zero", and line up reticule of slide with point $x = y = 0$ in. (see Fig. 27). Turn switch to "Calibrate", and line up

reticule with point x = 15 in., y = 10 in.. With "Pen Selector" at 1 and switch at "Zero", line up reticule with point at x = 8.5 in., y = 5 in.. Press "Pen Selector", and move to "Automatic". Turn switch to "Computer".

9. Prepare Magnetic Tape Unit for operation, and set switch to "Auto".

10. Insert Data Tape for ψ into Reader of Flexowriter and press "Start Read" lever. If the points to be plotted are those given on the Data Tape for ψ, press "Start Read" lever again after reading has stopped. Otherwise, type /1501/Y_I(Tab)Y_{II}(Tab)Y_{III}(Tab) with the desired values of Y_I, Y_{II}, Y_{III} for plotting and press "Start Read" lever. The computer then starts, reads subsequent data for ψ from paper tape, and stops after calculating the last value of ψ, namely, ψXmax, Ymax.

11. Set Tab Stops of Flexowriter to 6, 10, 15, 20 --- etc. to 85, and remove Carriage Return key. Depress "Punch On" lever. Press "Compute" button on control panel. Flexowriter will type out the Final Table of Results in the manner shown by Table VIII.

12. Restoring Commands. If for any reason the program is interrupted during the calculations of ϕ, prior to the printing out of the last value of ϕ (ϕXmax), the program for ϕ must be restored by setting up the command o//74f/s, and the Data Tape for ϕ must be re-entered, starting with the data for the first value of ϕ ($\phi_{X=1}$).
If the program for the calculation of ψ is interrupted, it must be restored by the command o//250f/s, and the Data Tape for ψ must be re-entered, starting with the data for the first value of ψ, namely, ψX = 1, Y = 1. The Data Tape for ϕ must not be re-entered in this case.

13. Commands affecting Operation of Magnetic Tape Unit. The command o/567f/s makes possible runs without using the Magnetic Tape Unit. If for successive runs the Magnetic Tape Unit is to be used again, set up o/570f/s, which restores the original program.

APPENDIX IV CODING OF PROGRAM FOR DATA REDUCTION WITH DIGITAL COMPUTER

Program for Calculation of Flow Coefficients ϕ

Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
0000	sm	30	1100	0310	0714	$(\Delta p'/100)$ Dec. to SR Dec./Oct.
0001	ut	34	3000	2100	0700	$(\Delta p'/100)$ Oct. in 2000
0002	ad	35	2000	2100	0300	
0003	sm	30	1101	0310	0714	$(p_1'/100)$ Dec. to SR Dec./Oct.
0004	ut	34	3000	2100	0700	$(p_1'/100)$ Oct. in 2000
0005	ad	35	2000	2100	0301	
0006	sm	30	1102	0310	0714	$(t_1/100)$ Dec. to SR Dec./Oct.
0007	ut	34	3000	2100	0700	$(t_1/100)$ Oct. in 2000
0010	ad	35	2000	2100	0302	
0011	sm	30	1103	0310	0714	$(t_a/100)$ Dec. to SR Dec./Oct.
0012	ut	34	3000	2100	0700	$(t_a/100)$ Oct. in 2000
0013	ad	35	2000	2100	0303	
0014	sm	30	1105	0310	0714	$(b/100)$ Dec. to SR Dec./Oct.
0015	ut	34	3000	2100	0700	$(b/100)$ Oct. in 2000
0016	ad	35	2000	2100	0304	
0017	sm	30	1106	0310	0714	$(N/10^4)$ Dec. to SR Dec./Oct.
0020	ut	34	3000	2100	0700	$(N/10^4)$ Oct. in 2000
0021	ad	35	2000	2100	0305	
0022	sm	30	1104	0310	0714	$(\Delta/100)$ Dec. to SR Dec./Oct.
0023	ut	34	3000	2100	0700	$(\Delta/100)$ Oct. in 2000
0024	su	36	0300	2000	0300	$(\Delta p/100)=(\Delta p'/100) - (\Delta/100)$
0025	su	36	0301	2000	0301	$(p_1/100)=(p_1'/100) - (\Delta/100)$
0026	mr	25	0300	0313	0321	$(\Delta p/100)\ c$
0027	mr	25	0301	0313	0322	$(p_1/100)\ c$
0030	ad	35	0304	0322	0324	$(b/100) + (p_1/100)\ c$
0031	dr	23	0321	0324	0323	I
0032	mr	25	1107	0323	0325	$(\varepsilon/2)\ I$
0033	su	36	0311	0325	0326	E
0034	sm	30	0322	0307	0327	$(1/2)\ (p_1/100)\ c$
0035	dr	23	0327	0304	0322	$(1/2)\ (p_1/100)\ c\ /\ (b/100)$
0036	ad	35	0311	0322	0331	F
0037	mr	25	0303	0314	0330	$(t_a/100)\ d$
0040	ad	35	0312	0330	0330	$(1/4) + (t_a/100)\ d$
0041	mr	25	0302	0315	0333	$(t_1/100)e$
0042	ad	35	0311	0333	0333	$(1/2) + (t_1/100)\ e$
0043	dr	23	0330	0333	0334	G
0044	dr	23	0320	0305	0336	H
0045	mr	25	0302	0317	0332	$(t_1/100)\ q$
0046	ad	35	0316	0332	0335	J
0047	mr	25	0323	0335	1020	I J to SR Square root
0050	ut	34	3000	2100	1000	$\sqrt{I\ J}$ in 2002
0051	mr	25	0336	2002	0337	$H\sqrt{I\ J}$
0052	mr	25	0334	0337	0334	$G\ H\sqrt{I\ J}$
0053	mr	25	0331	0334	0331	$F\ G\ H\sqrt{I\ J}$
0054	mr	25	0326	0331	0340	$E\ F\ G\ H\sqrt{I\ J}$
0055	mr	25	0340	1110	0335	$(\phi_o/10)\ E\ F\ G\ H\sqrt{I\ J}$
0056	sm	30	0335	0341	0342	$(\phi/10)$ Oct.
0057	ad	35	0342	2100	0744	$(\phi/10)$ Oct. to SR Oct./Dec.
0060	ut	34	3000	2100	0725	$(\phi/10)$ Dec. in 2000
0061	ad	35	2000	2100	0343	$(\phi/10)$ Dec. to 0343
0062	ex	32	0344	0347	0343	ϕ Dec. for printing $(.d_1\ d_2\ d_3\ d_4\ d_5)$
0063	pr	21	0343	0346	0001	prints ϕ Dec.
0064	ad	35	0342	2100	1200	$(\phi/10)$Oct. to channel 12, m_3 modified by 0067
0065	ad	35	0343	2100	1400	ϕ Dec. to channel 14, m_3 modified by 0070
0066	ad	35	0345	0350	0350	Counter X
0067	ad	35	0064	0345	0064	modifies m_3 of 0064
0070	ad	35	0065	0345	0065	modifies m_3 of 0065
0071	tm	34	1111	0350	0100	$X_{max} > X$?
			$X_{max} = X$			$X_{max} > X$
0072	ad	35	0351	0350	0353	sets up print command 0353
0073	ad	35	0352	0350	0355	sets up print command 0355
0074	su	36	0064	0350	0064	restores m_3 of 0064
0075	su	36	0065	0350	0065	restores m_3 of 0065
0076	ad	35	2100	2100	0350	sets X = 0
0077	ht	22	f	f	f	stop command
0100	fl	11	3000	3000	1100	reads new data from Flexowriter
0101	ut	34	3000	2100	0000	calculates $\phi(X+1)$, starting at 0000

Data Storage for Calculation of Pressure Coefficients Ψ

Mem. Cell	Sign	m_1	m_2	m_3	Remarks	
0200				f	Code z	
0201				f	Code R	
0202				f	h in inches of water	
0203				f	h_a in inches of water	Code S = 200
0204				f	t_a	
0205				f	b	
0206				f	N	
0207		7003	5135	6236	ζ = 0.8758906	
0210				f	Code z	
0211				f	Code R	
0212				f	h in inches of alcohol	
0213				f	h_a in inches of alcohol	Code S = 210
0214				f	t_a	
0215				f	b	
0216				f	N	
0217		5531	7752	7307	ζ = 0.7094714	
0220				f	Code z	
0221				f	Code R	
0222				f	h in cm. of water	
0223				f	h_a in cm. of water	Code S = 220
0224				f	t_a	
0225				f	b	
0226				f	N	
0227		2604	3725	4032	ζ = 0.3448461	
0230				f	Code z	
0231				f	Code R	
0232				f	h in cm. of alcohol	
0233				f	h_a in cm. of alcohol	Code S = 230
0234				f	t_a	
0235				f	b	
0236				f	N	
0237		2170	0734	7107	ζ = 0.2793253	

Auxiliary Commands

Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
0240	pr	21	0400	0241	0172	prints out Program for Ψ ,octal with address
0241	ht	22	f	f	f	
0242	pr	21	1300	0243	0072	prints out Number Storage for Ψ, octal with address
0243	ht	22	f	f	f	
0244	pr	21	1120	0245	0030	prints out Plotting Subroutine
0245	ht	22	f	f	f	
0246	pr	21	1611	0247	0040	prints out values of ($\Delta\Psi$/10) Oct. ,with address
0247	ht	22	f	f	f	
0250	ad	35	2100	2100	1341	sets Y = 0 } to restore Program for Ψ
0251	ut	34	3000	2100	0544	transfer to 0544 }
0252	pr	21	1504	0253	0037	prints out Subroutine for Preparation of Final Table of Results
0253	ht	22	f	f	f	
0254	pr	21	0600	0255	0062	prints out Number Storage for SR for Final Table of Results
0255	ht	22	f	f	f	

Number Storage for Calculation of Flow Coefficients Φ

Mem. Cell	Sign	m_1	m_2	m_3	Remarks
0300				f	(Δp'/100) Oct. by 0002 ; (Δp/100) by 0024
0301				f	(p_1'/100) Oct. by 0005 ; (p_1/100) by 0025
0302				f	(t_1/100) Oct. by 0010
0303				f	(t_a/100) Oct. by 0013
0304				f	(b/100) Oct. by 0016
0305				f	($N/10^4$) Oct. by 0021
0306	2	f	f	0004	shift right by 4 binary digits
0307	2	f	f	0001	shift right by 1 binary digit (multiply by 2)
0310				24	shift left by 20 binary digits

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Mem. Cell	Sign	m_1	m_2	m_3	Remarks
0311		4000	f	f	(1/2)
0312		2000	f	f	(1/4)
0313		167	0054	5614	c = 0.0290554
0314		336	7143	7544	d = 0.0544188
0315		675	6307	7311	e = 0.1088376
0316		1610	5240	6605	f = 0.2208653
0317		304	7304	4223	q = 0.0480769
0320		560	5075	3412	i = 0.09
0321				f	(Δ p/100) c by 0026
0322				f	(p_1/100) c by 0027 ; (1/2)(p_1/100) c/(b/100) by 0035
0323				f	I by 0031
0324				f	(b/100) + (p_1/100) c by 0030
0325				f	(ε /2) I by 0032
0326				f	E by 0033
0327				f	(1/2)(p_1/100) c by 0034
0330				f	(t_a/100) d by 0037 ; (1/4) + (t_a/100) d by 0040
0331				f	F by 0036 ; F G H $\sqrt{I\ J}$ by 0053
0332				f	(t_1/100) q by 0045
0333				f	(t_1/100) e by 0041 ; (1/2) + (t_1/100) e by 0042
0334				f	G by 0043 ; G H $\sqrt{I\ J}$ by 0052
0335				f	J by 0046 ; E F G H $\sqrt{I\ J}$ by 0055
0336				f	H by 0044
0337				f	H $\sqrt{I\ J}$ by 0051
0340				f	E F G H $\sqrt{I\ J}$ by 0054
0341				5	shift left by 5 binary digits(multiply by 2^5)
0342				f	(ϕ /10) Oct. by 0056
0343				f	(ϕ /10) Dec. by 0061 ; (ϕ) for printing by 0062
0344	16	7400	f	f	m_1 for command 0062
0345				1	Counting digit
0346	1	f	0001	f	Mode of print for (ϕ) Dec.,
0347	37	7400	f	f	m_2 for command 0062
0350				f	Counter X
0351	21	1200	2100	f	Print command for (ϕ/10) Oct. in channel 12
0352	21	1400	0346	f	Print command for (ϕ) Dec. in channel 14
0353				f	Print command set up by 0072,prints X cells of (ϕ/10) Oct.
0354	22	f	f	f	Stop command
0355				f	Print command set up by 0073,prints X cells of (ϕ) Dec.
0356	22	f	f	f	Stop command
0357	21	f	0360	0102	prints out Program for ϕ , octal with address
0360	22	f	f	f	
0361	21	0300	0362	0056	prints out Number Storage for ϕ , octal with address
0362	22	f	f	f	
0363	21	0700	0364	0023	prints out Subroutine:Conversion Dec./Oct. ,octal with address
0364	22	f	f	f	
0365	21	0725	0366	0021	prints out Subroutine:Conversion Oct./Dec., octal with address
0366	22	f	f	f	
0367	21	1000	0370	0021	prints out Subroutine:Square Root,octal with address
0370	22	f	f	f	

Program for Calculation of Pressure Coefficients ψ

Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
0400	ad	35	1301	2100	1305	sets up : S = 200 in 1305
0401	tm	34	0200	2100	0407	$z \neq 0$ in 0200 ?
		No data in S = 200				Data in S = 200
0402	ad	35	1300	1305	1305	S = 210
0403	tm	34	0210	2100	0407	$z \neq 0$ in 0210 ?
		No data in S = 210				Data in S = 210
0404	ad	35	1300	1305	1305	S = 220
0405	tm	34	0220	2100	0407	$z \neq 0$ in 0220 ?
		No data in S = 220				Data in S = 220 ; from 0500
0406	ad	35	1300	1305	1305	S = 230
		Data in S = 230				
0407	ad	35	1302	1305	0410	sets up S in m_3 of 0410

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Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
0410	bl	5	3000	3000	0200	8 cells to buffer, starting with S, m_3 modified by 0407
0411	bo	4	3000	3000	1310	cells (S – S + 7) to (1310 –1317)
0412	ad	35	1303	1305	0413	sets up m_3 = S in 0413
0413	ad	35	2100	2100	0200	sets z = 0 in cell S which was used for data input, m_3 modified by 0412
0414	tm	34	1310	1306	0417	z > 1 ?
	z=1: Manometer Board					z=2: Micro Manometer
0415	ad	35	1304	2100	0426	sets up: $(h_a/100)-(h/100)$ in 0426 for Manom. Board
0416	ut	34	3000	2100	0420	
0417	ad	35	1307	2100	0426	sets up: $(h/100)-(h_a/100)$ in 0426 for Micro Manom.
0420	sm	30	1312	1320	0714	(h/100) Dec. to SR Dec./Oct.
0421	ut	34	3000	2100	0700	(h/100) Oct. in 2000
0422	ad	35	2000	2100	1321	" to 1321
0423	sm	30	1313	1320	0714	$(h_a/100)$ Dec. to SR Dec./Oct.
0424	ut	34	3000	2100	0700	$(h_a/100)$ Oct. in 2000
0425	ad	35	2000	2100	1313	" to 1313
0426	su	36	1313	1321	1312	$L_B = (h_a/100) - (h/100)$ by 0415; or $L_M = (h/100) - (h_a/100)$ by 0417
0427	sm	30	1315	1320	0714	(b/100) Dec. to SR Dec./Oct.
0430	ut	34	3000	2100	0700	(b/100) Oct. in 2000
0431	dr	23	1323	2000	1315	M
0432	sm	30	1314	1320	0714	$(t_a/100)$ Dec. to SR Dec./Oct.
0433	ut	34	3000	2100	0700	$(t_a/100)$ Oct. in 2000
0434	mr	25	1325	2000	1314	$(t_a/100)$ n
0435	ad	35	1314	1324	1326	O
0436	sm	30	1316	1320	0714	$(N/10^4)$ Dec. to SR Dec./Oct.
0437	ut	34	3000	2100	0700	$(N/10^4)$ Oct. in 2000
0440	dr	23	1322	2000	2000	$1/(N/10^4)$
0441	mr	25	2000	2000	1327	W
0442	mr	25	1312	1315	1312	L M
0443	mr	25	1312	1326	1314	L M O
0444	mr	25	1314	1327	1313	L M O W
0445	mr	25	1313	1317	1317	L M O W
0446	sm	30	1317	1330	1331	$(\psi'/10)$ Oct.
0447	ad	35	1332	1311	0450	sets up command 0450
0450	ad	35	1331	1600	1331	$(\psi/10)=(\psi'/10)+(\Delta\psi/10)$, Oct., m_2 modified by 0447 acc. to Code R
0451	ad	35	1331	2100	0744	$(\psi/10)$ Oct. to SR Oct./Dec.
0452	ut	34	3000	2100	0725	$(\psi/10)$ Dec. in 2000
0453	ad	35	2000	2100	1333	$(\psi/10)$ Dec. Sign//$d_1 d_2 d_3 d_4$-----d_9
0454	ex	32	1334	1337	1333	extracts 00000//1111$d_2 d_3 d_4 d_5$-----d_9 bin.
0455	sm	30	1333	1336	1333	shifts 00000//00001111$d_2 d_3 d_4$---d_8 bin.
0456	ex	32	1333	1335	2000	(ψ) Dec. as Sign $d_1.\ d_2 d_3 d_4$---- d_8
0457	ad	35	2000	2100	1340	(ψ) Dec. to 1340
0460	ad	35	1306	1341	1341	Count Y
0461	tm	34	1341	1306	0464	Y > 1 ?
			Y = 1			Y > 1
0462	ad	35	1400	2100	0110	(ϕ) Dec. to 0110; m_1=140X by 0503; m_1=1400 by 0543
0463	ad	35	1200	2100	0130	$(\phi/10)$ Oct. to 0130; m_1= 120X by 0504; m_1= 1200 by 0544
0464	ad	35	1344	1341	0466	sets up command 0466
0465	ad	35	1345	1341	0467	sets up command 0467
0466	ad	35	1340	2100	0110	(ϕ) Dec. to cell 011Y ; m_3 modified by 0464
0467	ad	35	1331	2100	0130	$(\phi/10)$ Oct. to cell 013Y ; m_3 modified by 0465
0470	ut	34	3000	2100	0471	Dummy
0471	ts	17	2010	3000	0475	Test Switch 2010: down: prints ϕ once, and ψ for all Y's; up: no printing
	Test Switch 2010 down					Test Switch 2010 up
0472	tm	34	1341	1306	0474	Y > 1 ?
			Y = 1			Y > 1
0473	pr	21	0110	1346	0001	prints (ϕ) Dec. for Y = 1
0474	pr	21	1340	1346	0001	prints (ψ) Dec. for all values of Y
0475	ad	35	1306	1341	1347	Count Y + 1
0476	tm	34	1347	1500	0501	$Y + 1 > Y_{max}$?
	$Y+1 \leq Y_{max}$; $Y < Y_{max}$					$Y+1 > Y_{max}$; $Y=Y_{max}$
0477	fl	11	3000	3000	f	reads new data for ψ from Flexowriter
0500	ut	34	3000	2100	0400	calculates ψ(X,Y+1), starting at 0400
0501	ad	35	2100	2100	1341	sets Y = 0
0502	ad	35	1306	1350	1350	Count X
0503	ad	35	0462	1351	0462	changes m_1 of command 0462
0504	ad	35	0463	1351	0463	changes m_1 of command 0463

to 0400

from 0543

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Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
						to 0477
0505	dr	23	0130	1353	1352	$(\phi/10)/(0.3)$
0506	su	36	1352	1355	1352	$(\phi/10)/(0.3) - 0.1$
0507	dr	23	1352	1356	1354	ξ for plotting of ϕ
0510	ts	17	2020	3000	0516	Test Switch 2020 down: plots Y_I vs. ϕ with symbol o up: no plotting of Y_I
			Test Switch 2020 down			Test Switch 2020 up
0511	ad	35	1357	1501	0513	modifies m_1 of 0513
0512	ad	35	2100	2100	1143	sets up plotting symbol o in Plotting SR
0513	ad	35	0130	2100	1134	$(\psi/10)$ Oct. to Plotting SR, m_1 = $013Y_I$ by 0511
0514	ad	35	1354	2100	1135	ξ to Plotting Subroutine
0515	ut	34	3000	2100	1120	transfer to Plotting Subroutine
0516	ts	17	2040	3000	0524	Test Switch 2040 down: plots Y_{II} vs. ϕ with symbol · up: no plotting of Y_{II}
			Test Switch 2040 down			Test Switch 2040 up
0517	ad	35	1357	1502	0521	modifies m_1 of 0521
0520	ad	35	1145	2100	1143	sets up plotting symbol · in Plotting SR
0521	ad	35	0130	2100	1134	$(\psi/10)$ to Plotting SR, m_1 = $013Y_{II}$ by 0517
0522	ad	35	1354	2100	1135	ξ to Plotting Subroutine
0523	ut	34	3000	2100	1120	transfer to Plotting Subroutine
0524	ts	17	2100	3000	0532	Test Switch 2100 down: plots Y_{III} vs. ϕ with symbol + up: no plotting of Y_{III}
			Test Switch 2100 down			Test Switch 2100 up
0525	ad	35	1357	1503	0527	modifies m_1 of 0527
0526	ad	35	1144	2100	1143	sets up plotting symbol + in Plotting SR
0527	ad	35	0130	2100	1134	$(\psi/10)$ Oct. to Plotting SR; m_1 = $013Y_{III}$ by 0525
0530	ad	35	1354	2100	1135	ξ to Plotting Subroutine
0531	ut	34	3000	2100	1120	transfer to Plotting Subroutine
0532	tm	34	1350	1306	0534	X > 1 ?
			X=1			X > 1
0533	bs	14	3000	3000	0000	search for Block No. 00000 of Magnetic Tape
0534	bl	5	3000	3000	0110	transfers contents of cells 0110-0117 to Buffer 2000-2007
0535	wt	15	3000	3001	0000	writes contents of cells 0110-0117 on Magn. Tape, Sect.1, Block 2X-2
0536	sm	30	1600	1365	1600	time delay before new writing on tape
0537	bl	5	3000	300	0120	transfers contents of cells 0120-0127 to Buffer 2000-2007
0540	wt	15	3000	3001	0000	writes contents of cells 0120-0127 on Magn. Tape, Sect.1, Block 2X-1
0541	ad	35	1306	1350	1360	X+1
0542	tm	34	1360	1111	0544	$X + 1 > X_{max}$?
			$X+1<X_{max}; X < X_{max}$			$X+1 > X_{max}; X = X_{max}$
0543	ut	34	3000	2100	0477	transfer to 0477, calculates $\psi(X+1, Y=1)$
0544	ad	35	1361	2100	0462	restores command 0462 to original form
0545	ad	35	1362	2100	0463	restores command 0463 to original form
0546	ad	35	2100	2100	1350	restores X = 0
0547	ht	22	f	f	f	Stop computation

Preparation for typing of Final Table of Results if Magnetic Tape Unit was used for storage: Set Tab Stops of Flexowriter to 6, 10, 15, 20, etc to 85, removing Carriage Return key. To punch paper tape, press "Punch On" lever on Flexowriter. Press "Compute" button on control panel.

Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
0550	bs	14	3000	3000	0000	search for Block No. 00000 of Magnetic Tape
0551	ut	34	3000	2100	1504	transfer to Subroutine for Print Preparation of Final Table
0552	rt	16	3000	3001	0000	read 8 words in Block 2X-2 from tape to Buffer cells 2000-2007
0553	bo	4	3000	3000	0110	$\phi; \psi_1$ to ψ_7 to cells 0110 - 0117
0554	sm	30	1600	1365	1600	time delay before new reading from magnetic tape
0555	rt	16	3000	3000	0000	read 8 words in Block 2X-1 from tape to Buffer cells 2000-2007
0556	bo	4	3000	3000	0120	ψ_8 to ψ_{15} to cells 0120 - 0127
0557	pr	21	0110	1346	f	prints ϕ, ψ_1, ψ_2, --- ψ_Y ; m_3 modified by 0550
0560	pr	21	1364	1367	0001	returns carriage of Flexowriter
0561	ad	35	1306	1350	1350	Count X
0562	tm	34	1111	1350	0565	$X_{max} > X$?
			$X_{max} = X$			$X_{max} > X$
0563	ad	35	2100	2100	1350	restores X = 0
0564	ht	22	f	f	f	Stop of computation
0565	ut	34	3000	2100	0552	transfer to 0552 for printing remaining results from magn. tape
0566	ad	35	1370	2100	0532	modifies command 0532 to by-pass Magnetic Tape Unit
0567	ht	22	f	f	f	
0570	ad	35	1371	2100	0532	restores original command 0532 for operation with Magn. Tape Unit
0571	ht	22	f	f	f	

Kavra

Number Storage for Subroutine for Preparation of Final Table of Results

Mem. Cell	Sign	m_1	m_2	m_3	Remarks
0600		3646	3271	7751	(cap) F (low) l o w
0601		3436	6232	7745	(Car Ret) (cap) C (low) o e
0602		4646	2712	1231	f f . del del del del
0603		1212	1212	1231	del del del del del tab
0604				4	Y_{max} = 4 (Dec.)
0605				6	Y_{max} = 6 (Dec.)
0606				10	Y_{max} = 8 (Dec.)
0607				12	Y_{max} = 10 (Dec.)
0610				14	Y_{max} = 12 (Dec.)
0611				16	Y_{max} = 14 (Dec.)
0612	10	f	f	f	Alphabetic Mode of Print
0613		3670	3263	4544	Cap P low r e s
0614		4440	6345	6436	s u r e space cap
0615		6232	7745	4646	C low o e f f
0616		6062	6045	6675	i c i e n t
0617		4434	3431	1212	s CarRet CarRet tab del del
0620		6464	6436	5423	space space space cap Y =
0621		3271	3112	1212	low 1 tab del del del
0622		6464	6436	5423	space space space cap Y =
0623		3200	3112	1212	low 2 tab del del del
0624		6464	6436	5423	space space space cap Y =
0625		3201	3121	1212	low 3 tab del del del
0626		6464	6436	5423	space space space cap Y =
0627		3204	3112	1212	low 4 tab del del del
0630		6464	6436	5423	space space space cap Y =
0631		3207	3112	1212	low 5 tab del del del
0632		6464	6436	5423	space space space cap Y =
0633		3206	3112	1212	low 6 tab del del del
0634		6464	6436	5423	space space space cap Y =
0635		3203	3112	1212	low 7 tab del del del
0636		6464	6436	5423	space space space cap Y =
0637		3205	3112	1212	low 8 tab del del del
0640		6464	6436	5423	space space space cap Y =
0641		3253	3112	1212	low 9 tab del del del
0642		6464	6436	5423	space space space cap Y =
0643		3271	5231	1212	low 10 tab del del
0644		6464	6436	5423	space space space cap Y =
0645		3271	7131	1212	low 11 tab del del
0646		6464	6436	5423	space space space cap Y =
0647		3271	0031	1212	low 12 tab del del
0650		6464	6436	5423	space space space cap Y =
0651		3271	0131	1212	low 13 tab del del
0652		6464	6436	5423	space space space cap Y =
0653		3271	0431	1212	low 14 tab del del
0654		6464	6436	5423	space space space cap Y =
0655		3271	0712	1212	low 15 del del del
0656	21	0620	0612	f	to set up print command 1533
0657				f	Dummy
0660		3434	1234	3412	CarRet CarRet del CarRet CarRet del
0661				f	2 Y_{max} by 1531 for command 1533

Auxiliary Tape No. 1 for Data measured with Orifice 11.5 in. Diameter

Mem. Cell	Sign	m_1	m_2	m_3	Remarks
1100				f	(Δ p') cm. water (Decimal)
1101				f	(p_1') cm. water (Decimal)
1102				f	(t_1) °F (Decimal)
1103				f	(t_a) °F (Decimal)
1104				f	(Δ) cm. water (Decimal)
1105				f	(b) in. Hg (Decimal)
1106				f	(N) rpm (Decimal)
1107		1166	2775	4256	(ε /2) = 0.1539
1110		1174	6224	4612	(ϕ_o/10) = 0.1554654
1111				f	X_{max} (Octal)

Vavra

Auxiliary Tape No.2 for Data measured with Orifice 13.5 in. Diameter

Mem. Cell	Sign	m_1	m_2	m_3	Remarks
1100				f	(same as Auxiliary Tape No.1)
1101				f	
1102				f	
1103				f	
1104				f	
1105				f	
1106				f	
1107		1222	0133	6002	$(\varepsilon/2) = 0.16165$
1110		1610	4536	5617	$(\phi_o/10) = 0.2208461$
1111				f	X_{max} (Octal)

Auxiliary Tape No.3 for Data measured with Orifice 15.0 in. Diameter

Mem. Cell	Sign	m_1	m_2	m_3	Remarks
1100				f	(same as Auxiliary Tape No.1)
1101				f	
1102				f	
1103				f	
1104				f	
1105				f	
1106				f	
1107		1274	6465	5206	$(\varepsilon/2) = 0.1711$
1110		2343	7035	3440	$(\phi_o/10) = 0.3056353$
1111				f	X_{max} (Octal)

Subroutine for Plotting Ψ vs. ϕ on Digital Plotter

Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
1120	sl	27	3000	1132	2000	prepare exit to next cell of main program
1121	ex	32	2000	1133	1131	
1122	su	36	1134	1137	1134	$(\Psi/10) - 0.04$
1123	dr	23	1134	1140	1134	$\eta = ((\Psi/10) - 0.04)/0.128$
1124	sl	27	1134	1141	1134	η shifted right by 11 binary digits
1125	ex	32	1134	1142	1135	extracts η into ξ of 1135
1126	ex	32	1143	1147	1135	extracts symbol selector into m_1 of command 1127
1127	pl	20	1135	3000	f	plotting command, plots η vs. ξ
1130	sm	30	2000	1136	2000	time delay of 1.8 sec till next plot
1131	ut	34	3000	2100	f	transfers to next cell of main program from which SR was entered
1132		2	f	f	30	shift right by 24 binary digits
1133					7777	extractor
1134					f	$(\Psi/10)$ introduced prior to entry; $(\Psi/10) - 0.04$ by 1123; η by 1124
1135					f	ξ introduced prior to entry; ξ by 1125; m_1 for 1127 by 1126
1136					4400	shifts left by 2304 binary digits
1137			243	6560	5075	0.04 (Decimal)
1140			1014	2233	5136	0.128 (Decimal)
1141		2	f	f	0013	shifts right by 11 binary digits
1142			7	7770	f	m_2 for command 1125
1143					f	m_1 for command 1126
1144				20	f	plots points as +
1145				10	f	Plotting Symbol plots points as •
1146					f	Selector,set up in 1143 plots points as o
1147				30	f	m_2 for command 1126

Vavra

Number Storage for Calculation of Ψ

Mem. Cell	Sign	m_1	m_2	m_3	Remarks
1300				10	Marker for Selector of Code S
1301				200	Original Code S
1302	5	3000	3000	f	to set up command 0410 by 0407
1303	35	2100	2100	f	to set up command 0413 by 0412
1304	36	1313	1321	1312	command 0426 for Manometer Board
1305				f	Code S
1306				1	Comparator for Code z ; Counter
1307	36	1321	1313	1312	command 0426 for Micro Manometer
1310				f	Code z
1311				f	Code R
1312				f	h — L_B or L_M by 0426 ; L M by 0442
1313				f	h_a — introduced by 0411 — $(h_a/100)$ by 0425 ; L M O W by 0444
1314				f	t_a — $(t_a/100)$ by 0434 ; L M O by 0443
1315				f	b — M by 0431
1316				f	N
1317				f	ξ — L M O W by 0445
1320				24	shift left by 20 binary digits
1321				f	(h/100) by 0422
1322		560	5075	3412	i = 0.09
1323		1144	6057	4070	l = 0.1496
1324		3421	2503	2742	m = 0.4417307
1325		611	6611	0446	n = 0.0961538
1326				f	O by 0435
1327				f	W by 0441
1330				4	shift left by 4 binary digits (multiply by 2^4)
1331				f	$(\Psi'/10)$ Oct. by 0446 ; $(\Psi/10)$ Oct. by 0450
1332	35	1331	1600	1331	to set up command 0447 ; m_2 changed to code R
1333				f	$(\Psi/10)$ Dec. by 0453 ; extracted by 0454 ; shifted by 0455
1334		7400	f	f	m_1 for extract command 0454
1335		377	7777	7777	m_2 for extract command 0456
1336	2	f	f	0004	shift right by 4 binary digits
1337	37	7400	f	f	m_2 for extract command 0454
1340				f	Ψ Dec. Sign//$d_1.d_2d_3d_4$----d_8 by 0457
1341				f	Count Y by 0460 ; Y = 0 by 0501
1342	35	1400	2100	0110	to restore command 0462
1343	35	1200	2100	0130	to restore command 0463
1344	35	1340	2100	0110	to change command 0466 by 0463
1345	35	1331	2100	0130	to change command 0467 by 0464
1346	1	f	0001	f	Dec. Mode of print $(\phi = .d_1d_2\text{--}d_5\ ;\ \Psi = d_1.d_2d_3\text{-}\ d_5)$
1347				f	Y + 1 by 0475
1350				f	Count X by 0502 or 0557 ; X = 0 by 0545 or 0563
1351		1	f	f	Marker for change of command 0462
1352				f	$(\phi/10)/0.3$ by 0505 ;$((\phi/10)/0.3)$ - 0.1 by 0506
1353		2314	6314	6314	0.3 (Decimal)
1354				f	ξ for plotting ϕ by 0507
1355		631	4631	4631	0.1 (Decimal)
1356		1273	0317	4171	0.1706667 (Decimal)
1357	35	0130	2100	1134	to change command 0513 by 0511
1360				f	Count X + 1 by 0540
1361	35	1400	2100	0110	original command 0462 restored by 0544
1362	35	1200	2100	0130	original command 0463 restored by 0545
1363	21	0110	1346	f	to set up print command 0577 by 1504
1364		1212	1212	1234	Alphabetic code for carriage return
1365				200	shift for time delay by commands 0536 and 0554
1366				f	Dummy
1367	10	f	f	f	Alphabetic mode of print
1370	34	3000	2100	0541	to modify command 0532 by 0566 to by-pass Magnetic Tape Unit
1371	34	1350	1306	0534	original command 0532 for operation with Magn. Tape Unit,restored by 0570

Auxiliary Data for Calculation of Ψ

Mem. Cell	Sign	m_1	m_2	m_3	Remarks
1500				f	Y_{max}
1501				f	Y_I to be plotted with symbol o
1502				f	Y_{II} to be plotted with symbol •
1503				f	Y_{III} to be plotted with symbol +

Vavra

Subroutine : Print Preparation of Final Table of Results

Mem. Cell	Op'n	Op'n Code	m_1	m_2	m_3	Remarks
1504	ad	35	1363	1347	0557	sets up print command in 0557 , m_3 = Y + 1
1505	pr	21	0600	0612	0004	prints "Flow" CarRet "Coeff." tab
1506	tm	34	1500	0604	1510	$Y_{max} > 4$?
			$Y_{max} \leqslant 4$			$Y_{max} > 4$
1507	ut	34	3000	2100	1531	
1510	pr	21	0603	0612	0001	1st tab
1511	tm	34	1500	0605	1513	$Y_{max} > 6$?
			$Y_{max} \leqslant 6$			$Y_{max} > 6$
1512	ut	34	3000	2100	1531	
1513	pr	21	0603	0612	0001	2nd tab
1514	tm	34	1500	0606	1516	$Y_{max} > 8$?
			$Y_{max} \leqslant 8$			$Y_{max} > 8$
1515	ut	34	3000	2100	1531	
1516	pr	21	0603	0612	0001	3rd tab
1517	tm	34	1500	0607	1521	$Y_{max} > 10$?
			$Y_{max} \leqslant 10$			$Y_{max} > 10$
1520	ut	34	3000	2100	1531	
1521	pr	21	0603	0612	0001	4th tab
1522	tm	34	1500	0610	1524	$Y_{max} > 12$?
			$Y_{max} \leqslant 12$			$Y_{max} > 12$
1523	ut	34	3000	2100	1531	
1524	pr	21	0603	0612	0001	5th tab
1525	ut	34	3000	2100	1526	Dummy
1526	tm	34	1500	0611	1530	$Y_{max} > 14$?
			$Y_{max} \leqslant 14$			$Y_{max} > 14$
1527	ut	34	3000	2100	1531	
1530	pr	21	0603	0612	0001	6th tab
1531	sm	30	1500	1306	0661	2 Y_{max}
1532	pr	21	0613	0612	0005	prints "Pressure Coefficients" CarRet tab
1533	ad	35	0656	0661	1534	modifies m3 of 1534 to 2 Y_{max}
1534	pr	21	0620	0612	f	prints Y = 1 to Y = Y_{max}
1535	pr	21	0660	0612	0001	4 CarRet
1536	ut	34	3000	2100	0552	transfer to main program

Values of $\Delta\Psi/10$ (Oct.) for Pressure Taps of Rotor Blades

Mem. Cell	Sign	m_1	m_2	m_3	$\Delta\Psi$ /10 (Dec.)	Quadrant	Tap No.
1611		250	6672	3204	0.0412251	1	1P13
1612		164	2625	1530	0.0284055	1	1P12
1613		626	1373	3575	0.0991666	1	1P35
1614		241	6572	3104	0.0395123	1	1S13
1615		160	2555	7741	0.0274266	1	1S12
1616		207	7207	6125	0.0331807	1	1P21
1617		612	3645	6275	0.0963081	1	1S35
1620		206	0432	6321	0.0327317	1	1S21
1621		353	5445	0111	0.0575431	2	2P33
1622		471	1553	4043	0.0764682	2	2P34
1623		603	3277	5373	0.0945854	2	2P25
1624		345	1140	7536	0.0559445	2	2S33
1625		466	5411	3065	0.0758520	2	2S34
1626		131	4473	5135	0.0218694	2	2P11
1627		563	2272	0677	0.0906483	2	2S25
1630		130	6033	1275	0.0216691	2	2S11
1631		561	5127	4644	0.0902457	3	3P15
1632		323	5563	3471	0.0516884	3	3P23
1633		271	6702	7500	0.0453760	3	3P32
1634		441	3153	3705	0.0706546	3	3P24
1635		311	6466	6721	0.0492739	3	3S23
1636		535	7005	0067	0.0854190	3	3S15
1637		273	0220	2542	0.0456629	3	3S32

Mem. Cell	Sign	m_1	m_2	m_3	$\Delta\Psi/10$ (Dec.)	Quadrant	Tap No.
1640		423	5475	6073	0.0673102	3	3S24
1641		312	5101	4171	0.0494729	4	4P23
1642		224	0455	6174	0.0361508	4	4P22
1643		410	3277	5044	0.0645561	4	4P14
1644		304	6107	0007	0.0480389	4	4S23
1645		250	3702	0014	0.0411340	4	4P31
1646		225	6477	3543	0.0365791	4	4S22
1647		370	4716	2250	0.0606965	4	4S14
1650		255	7346	5254	0.0424637	4	4S31 Kavra

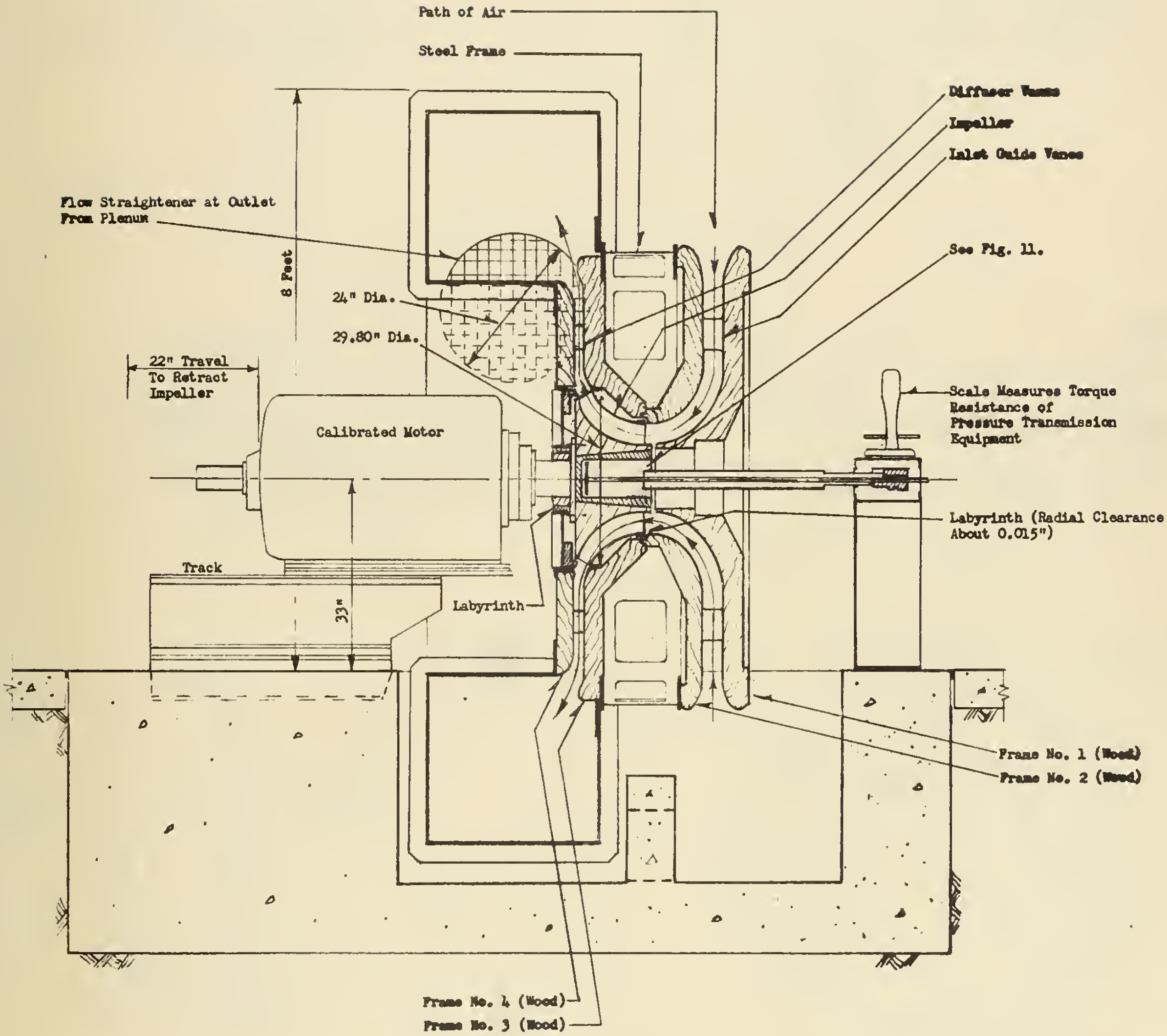


FIG. I — SECTION THROUGH TEST RIG

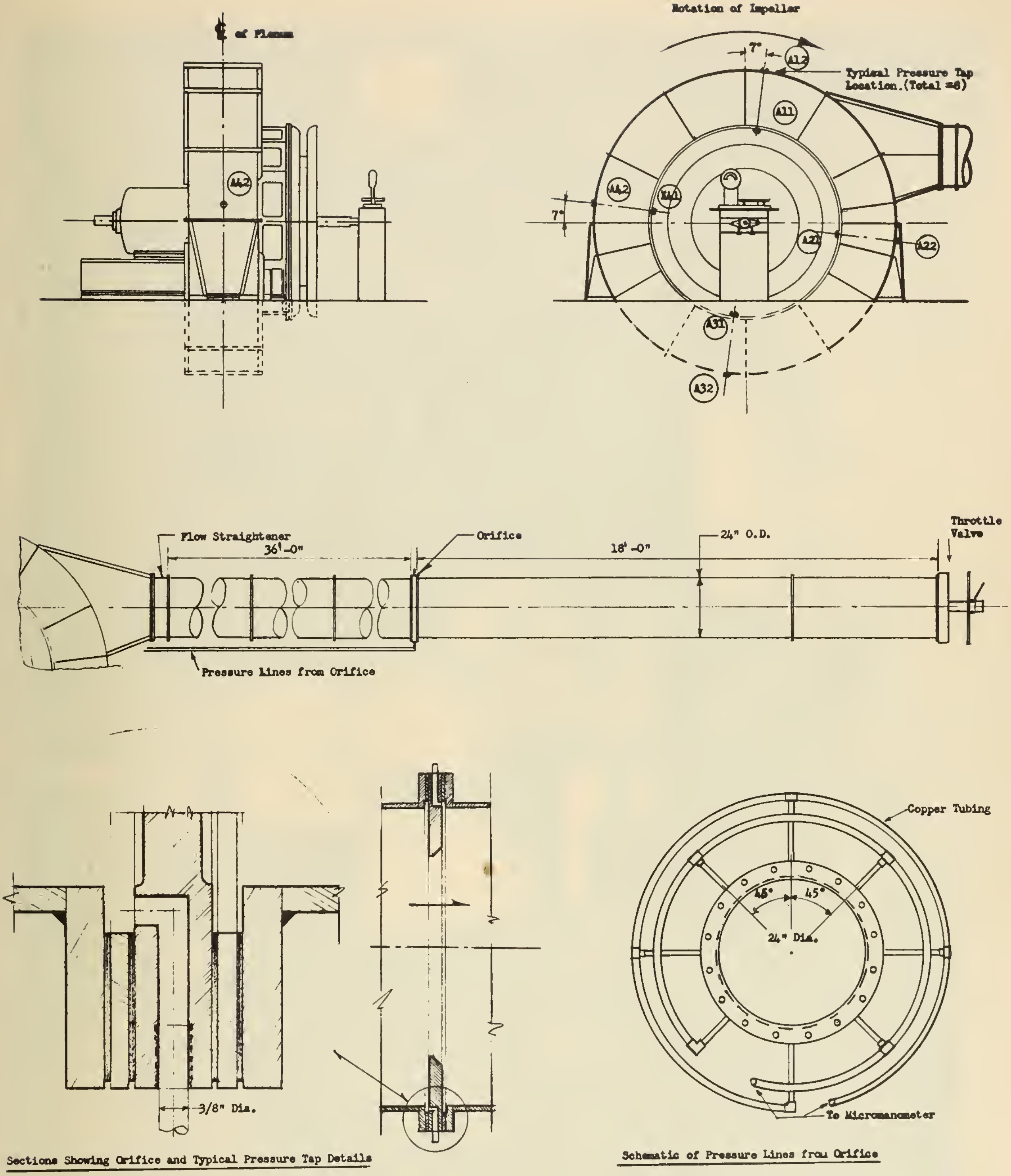


FIG. 2 — PLENUM CHAMBER AND DISCHARGE PIPE

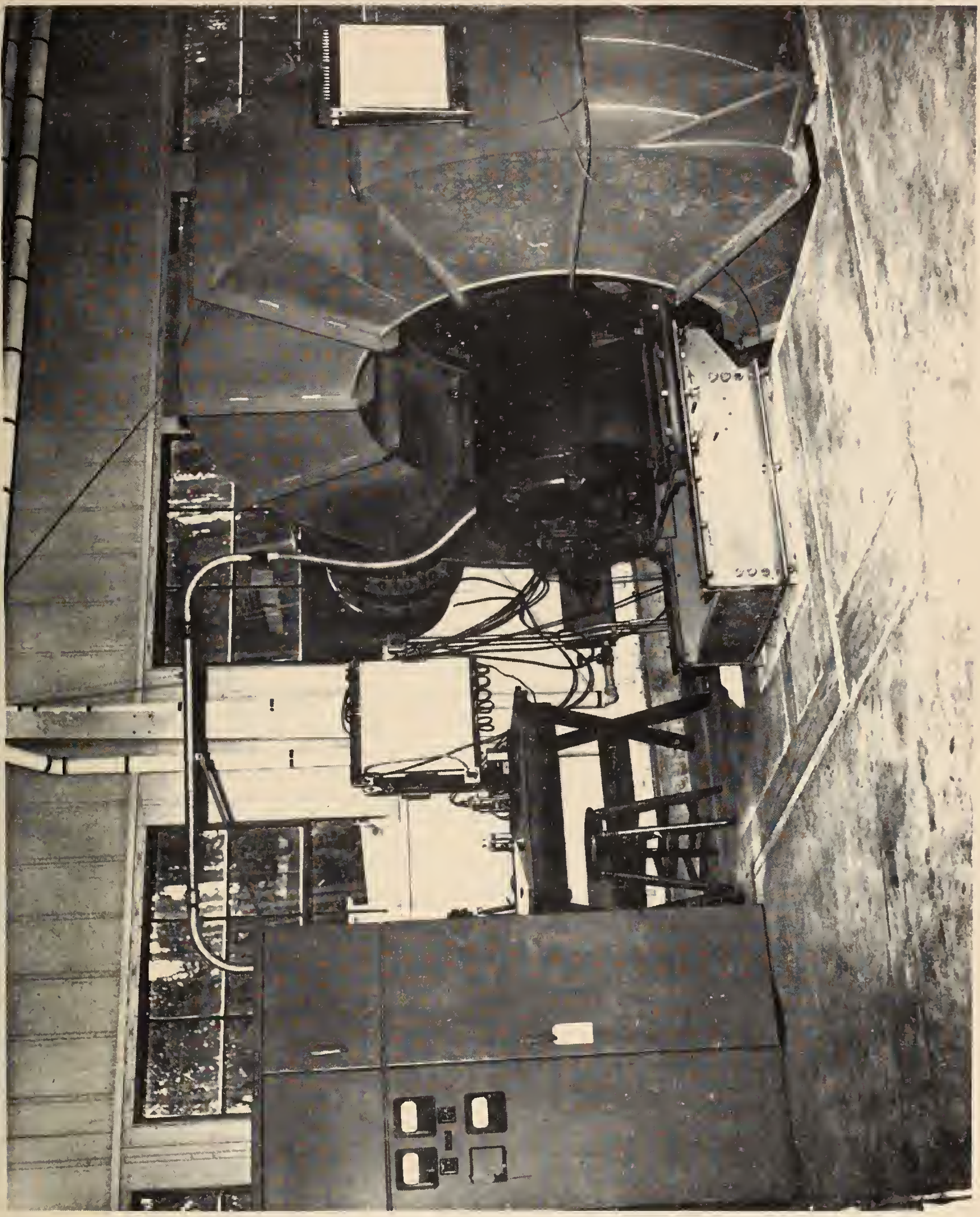


FIG. 3 VIEW OF MOTOR SIDE

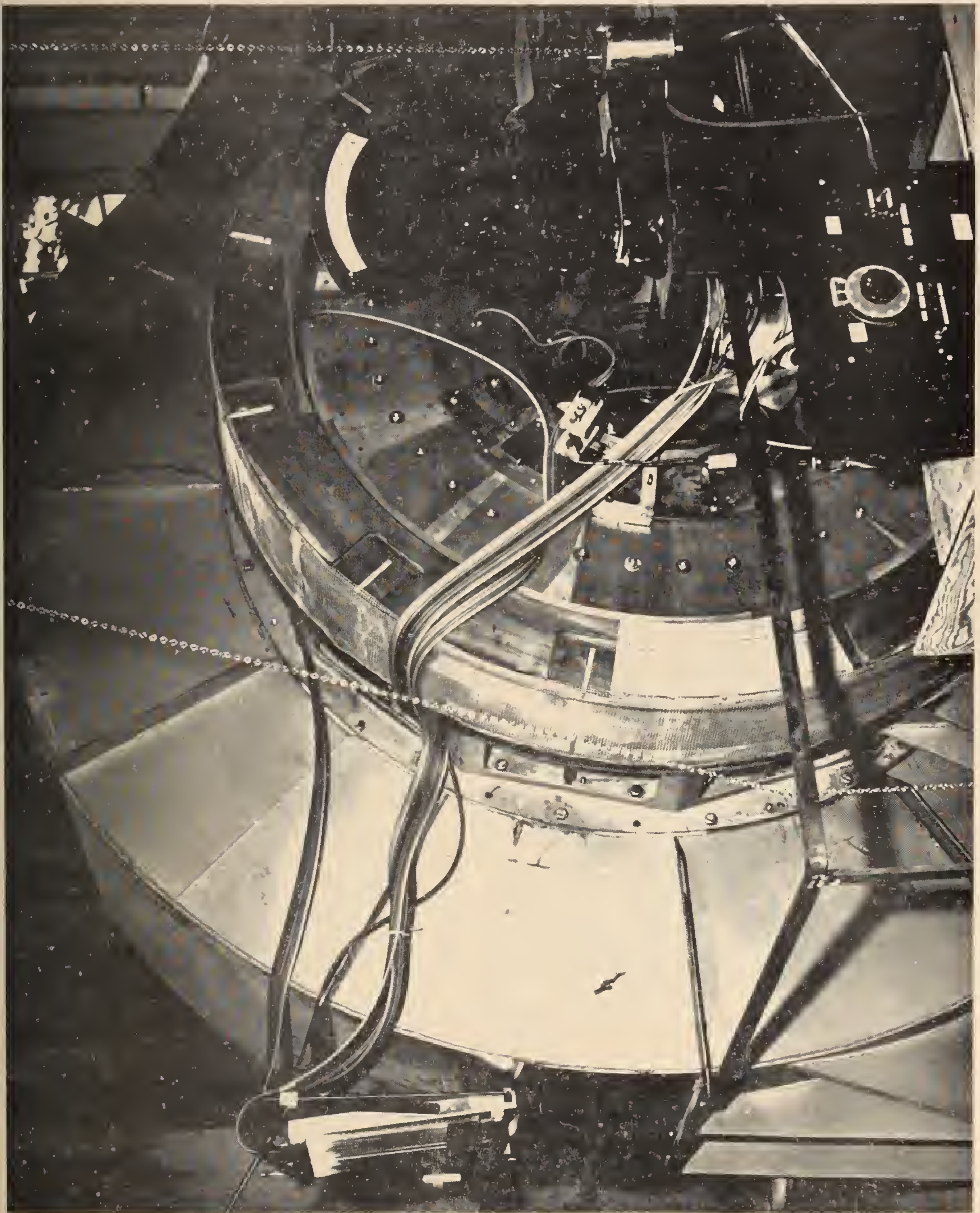


FIG. 4 VIEW OF INLET SIDE

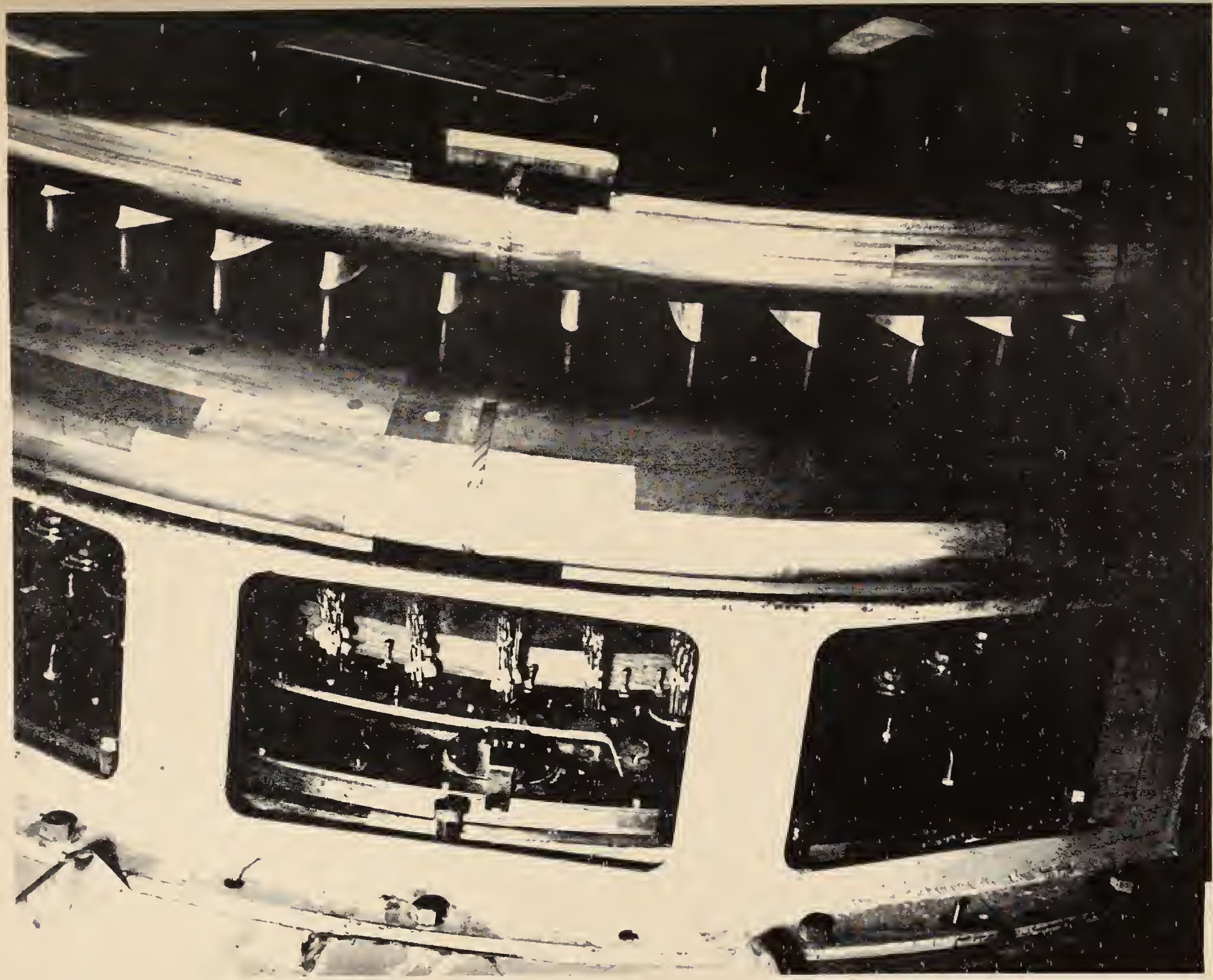


FIG. 5 SIDE VIEW SHOWING INLET GUIDE VANES AND PRESSURE LEADS FROM DIFFUSER VANES

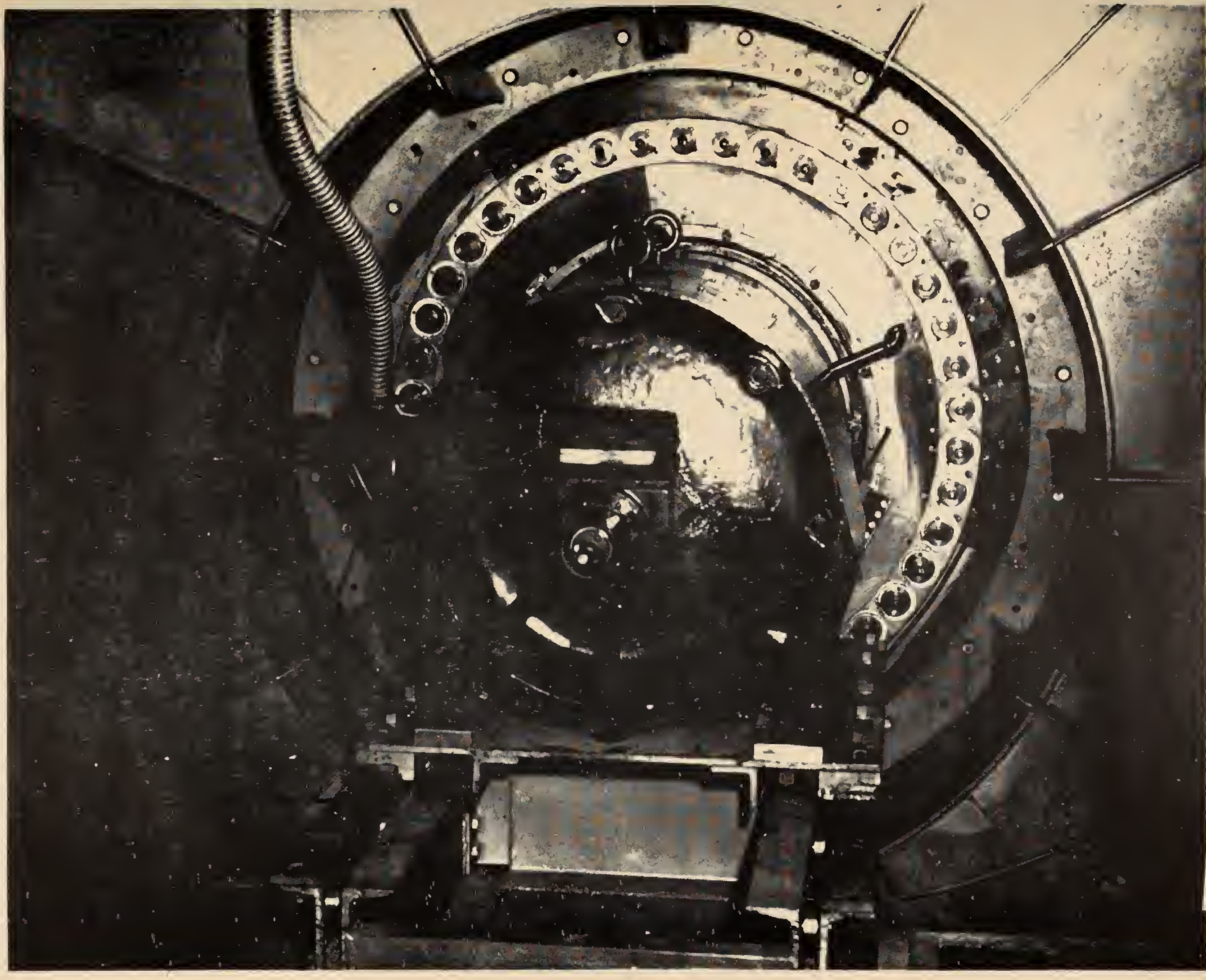


FIG. 6 MOTOR AND ADJUSTING DEVICE OF DIFFUSER VANES

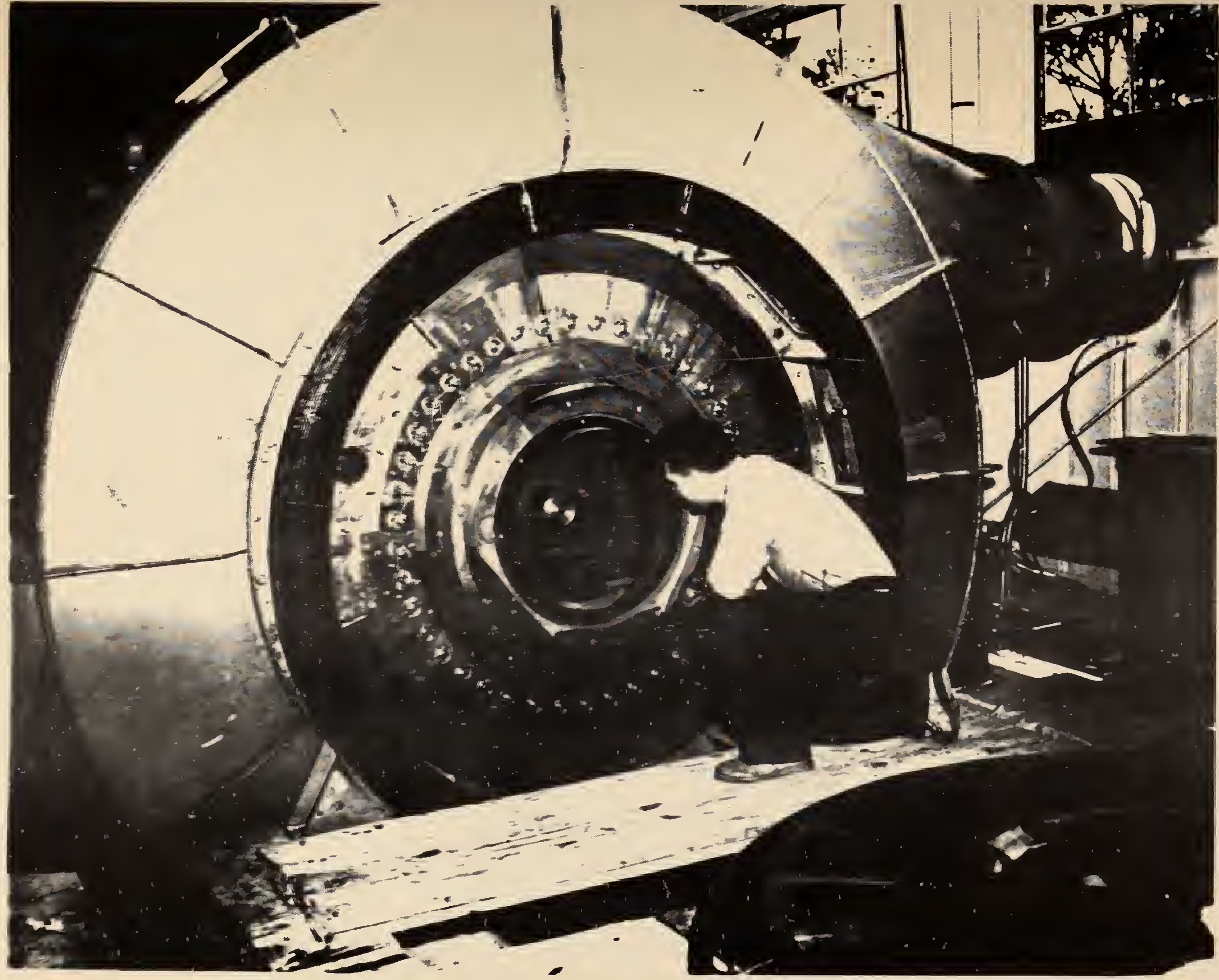


FIG. 7 TEST RIG DURING ERECTION, BEFORE INSTALLATION OF INLET FRAMES AND IMPELLER

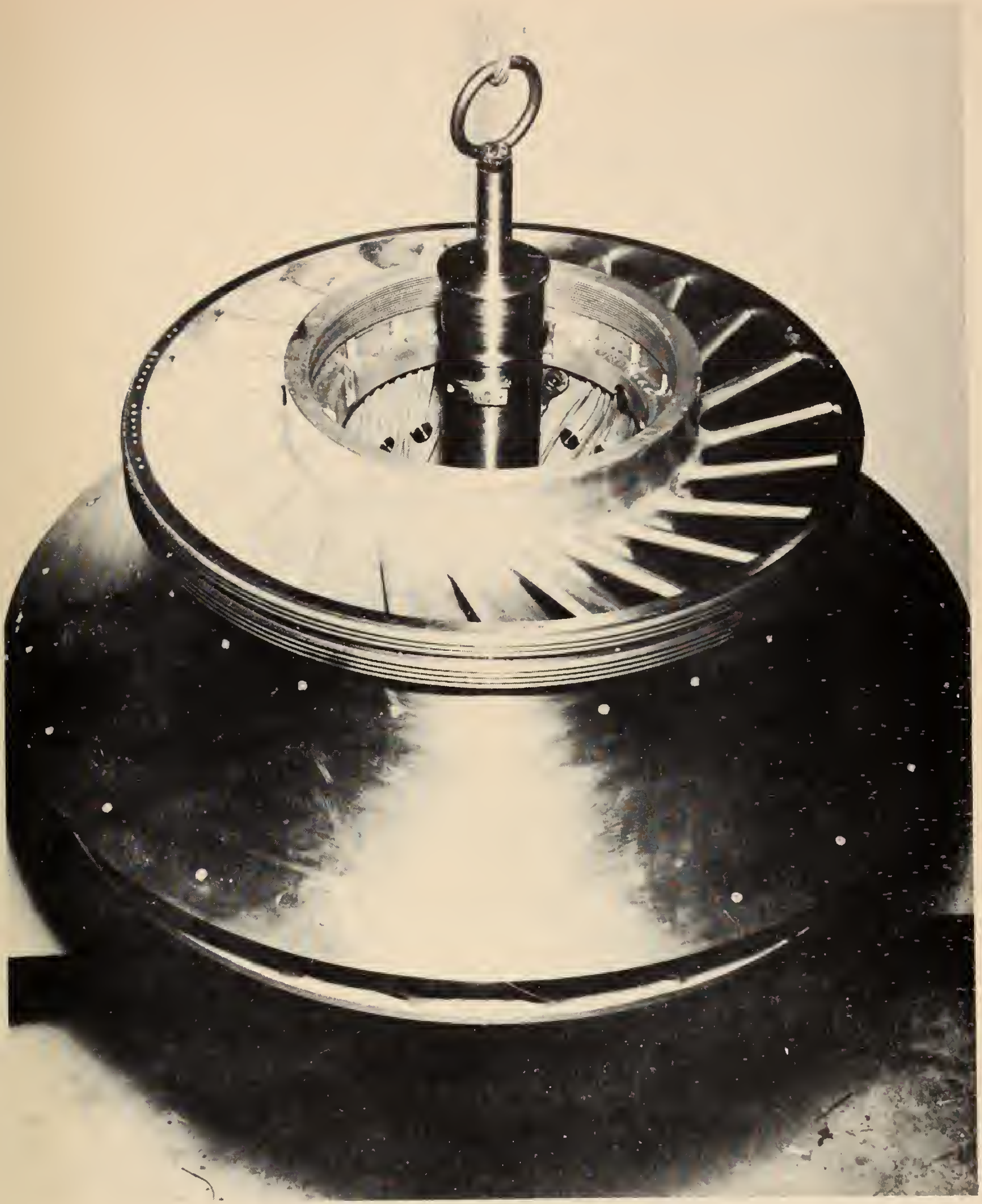


FIG. 8 ROTOR, VIEW OF INLET

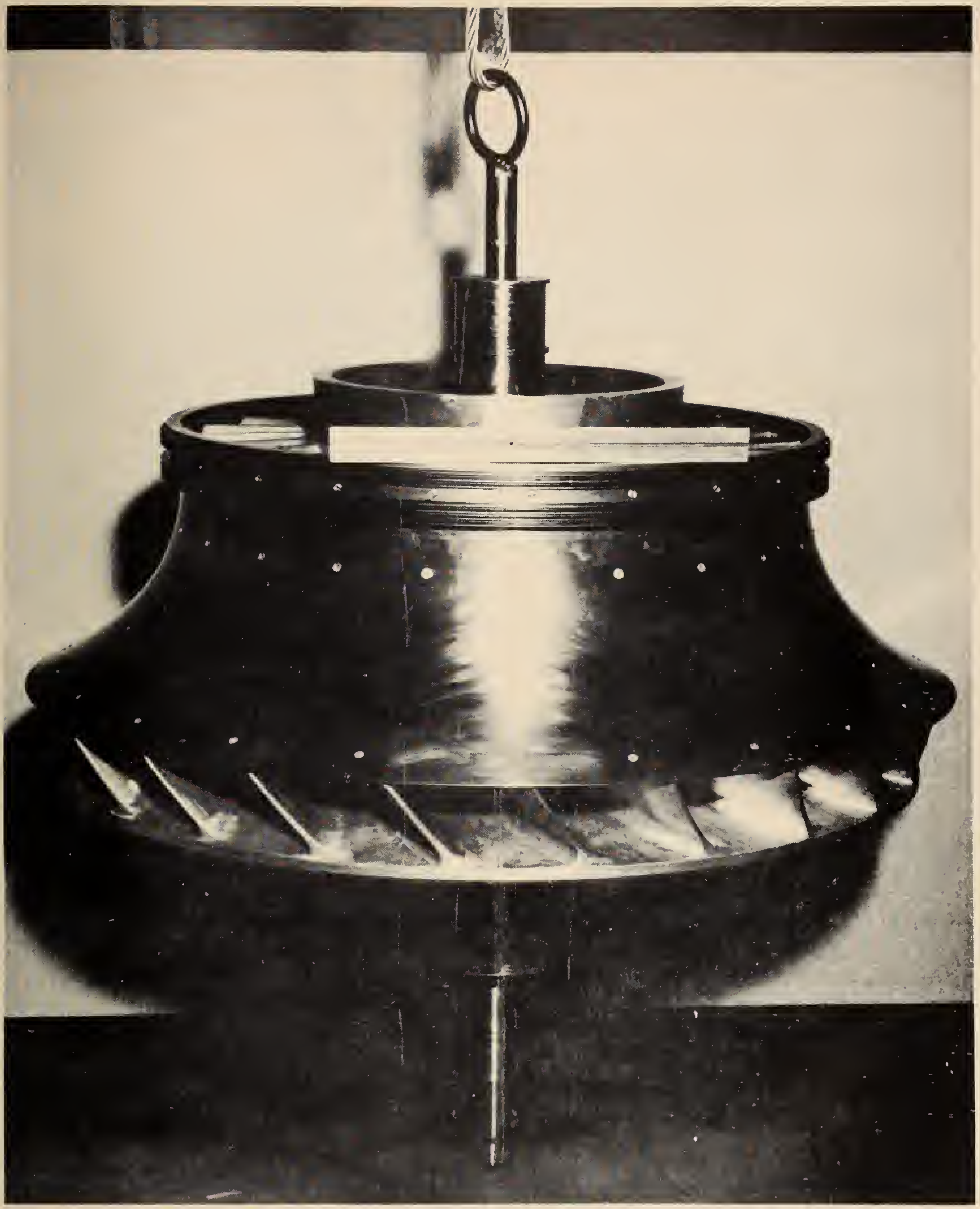


FIG. 9 ROTOR, SIDE VIEW

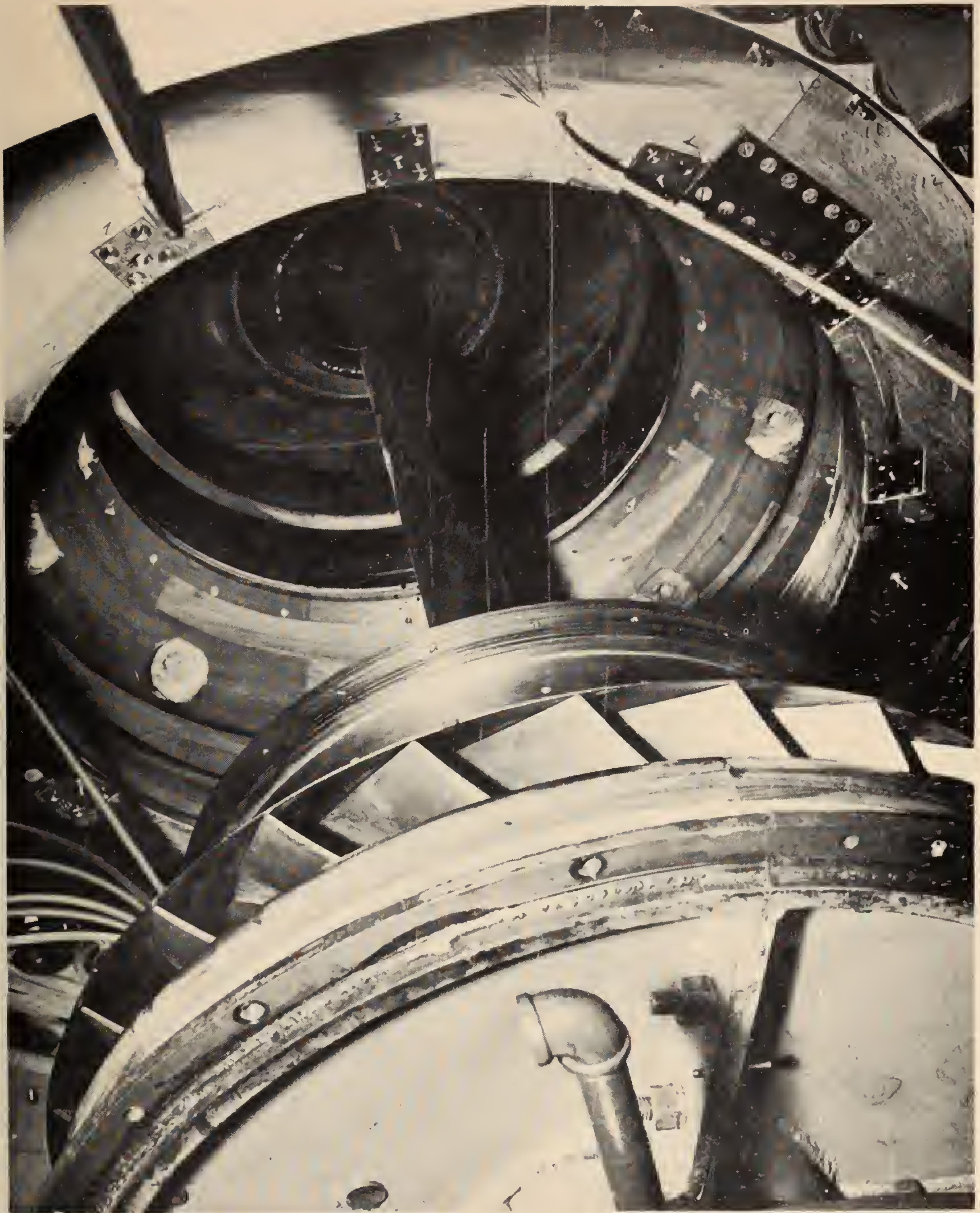


FIG. 10 VIEW FROM MOTOR SIDE WITH IMPELLER RETRACTED

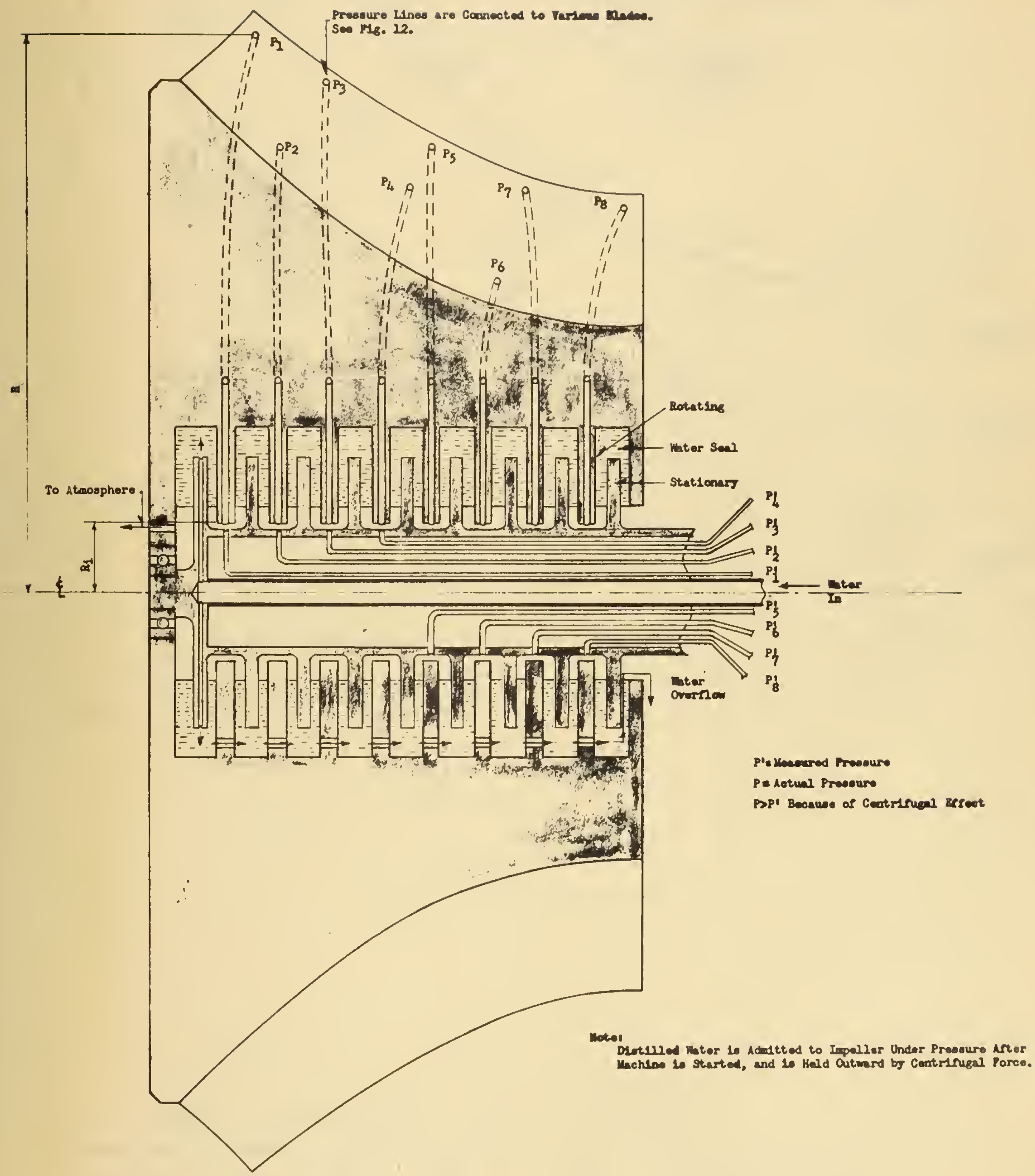
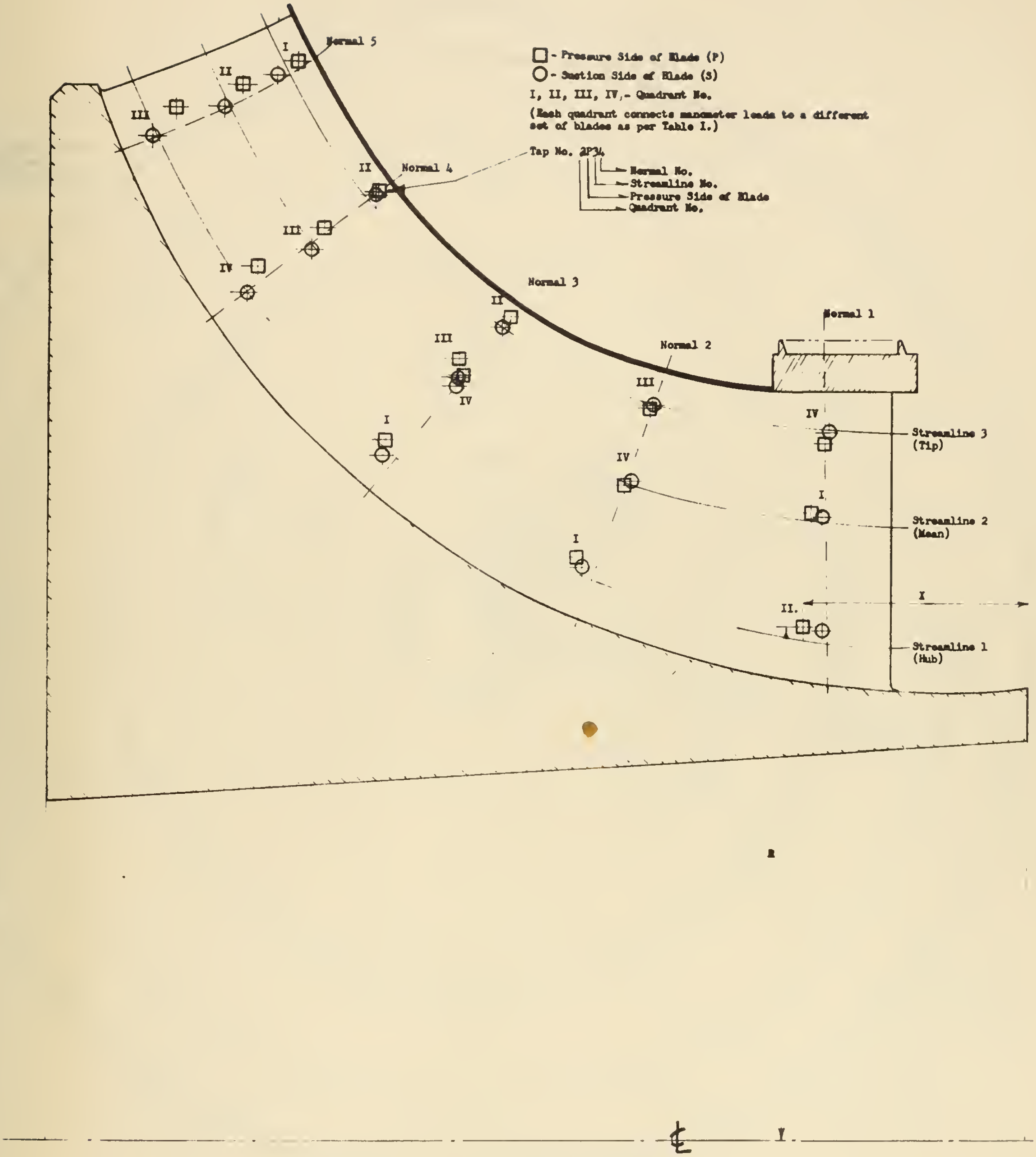


FIG. 11 — SCHEMATIC OF PRESSURE TRANSMISSION SYSTEM OF IMPELLER



Manometer No.'s vs. Pressure Tap No.'s

Manometer No.	Quadrant I	Quadrant II	Quadrant III	Quadrant IV
1	1P13	2P33	3P15	4P23
2	1P12	2P34	3P23	4P22
3	1P35	2P25	3P32	4P14
4	1S13	2S33	3P24	4S23
5	1S12	2S34	3S23	4P31
6	1P21	2P11	3S15	4S22
7	1S35	2S25	3S32	4S14
8	1S21	2S11	3S24	4S31

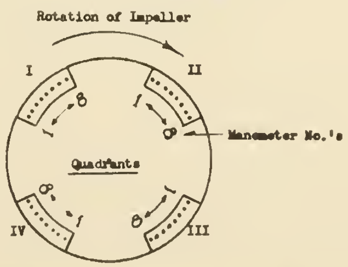


FIG. 12 — PRESSURE TAP NUMBERING SYSTEM FOR IMPELLER

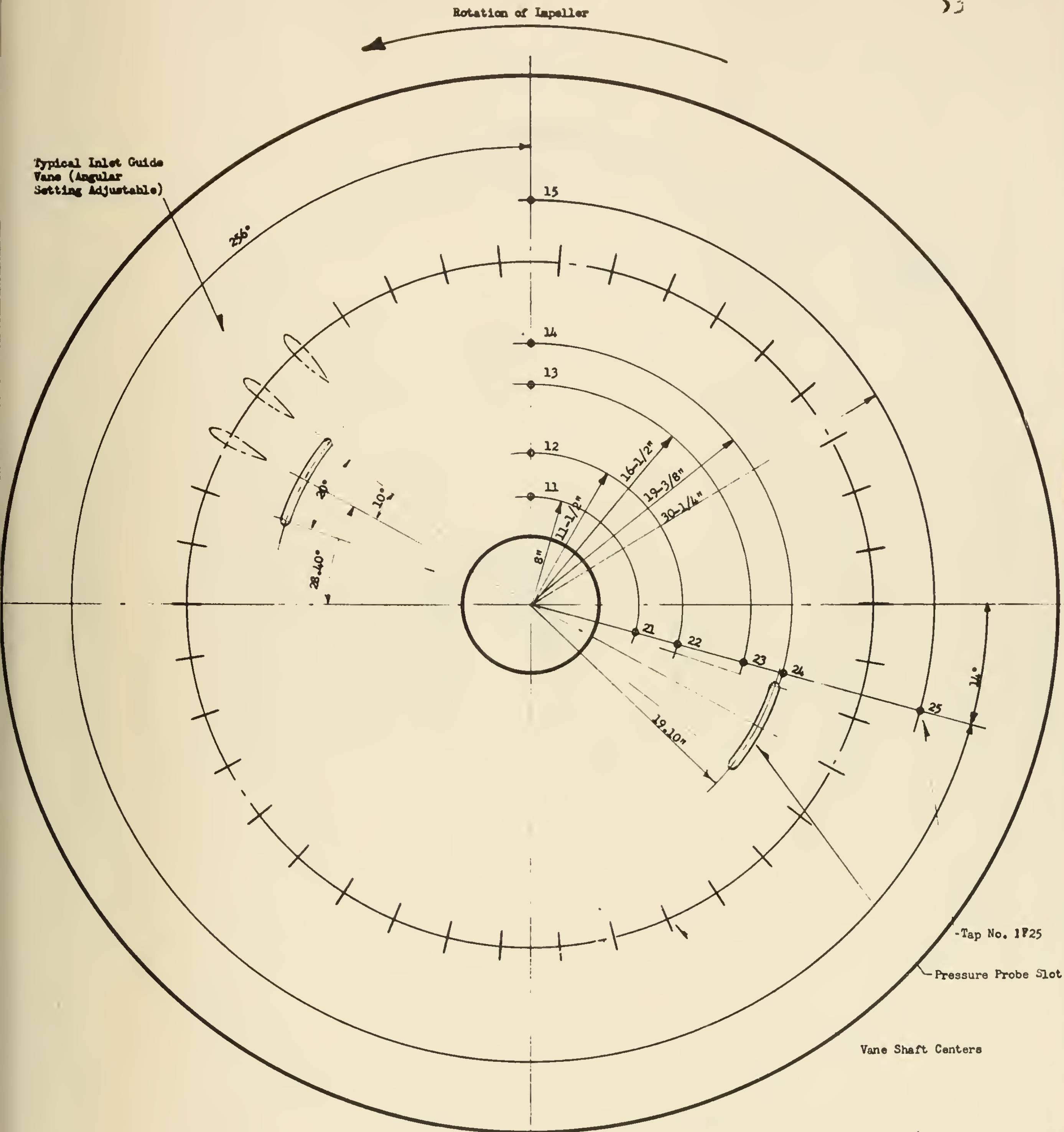


FIG. 13 — WALL PRESSURE TAPS AT FRAME NO. 1

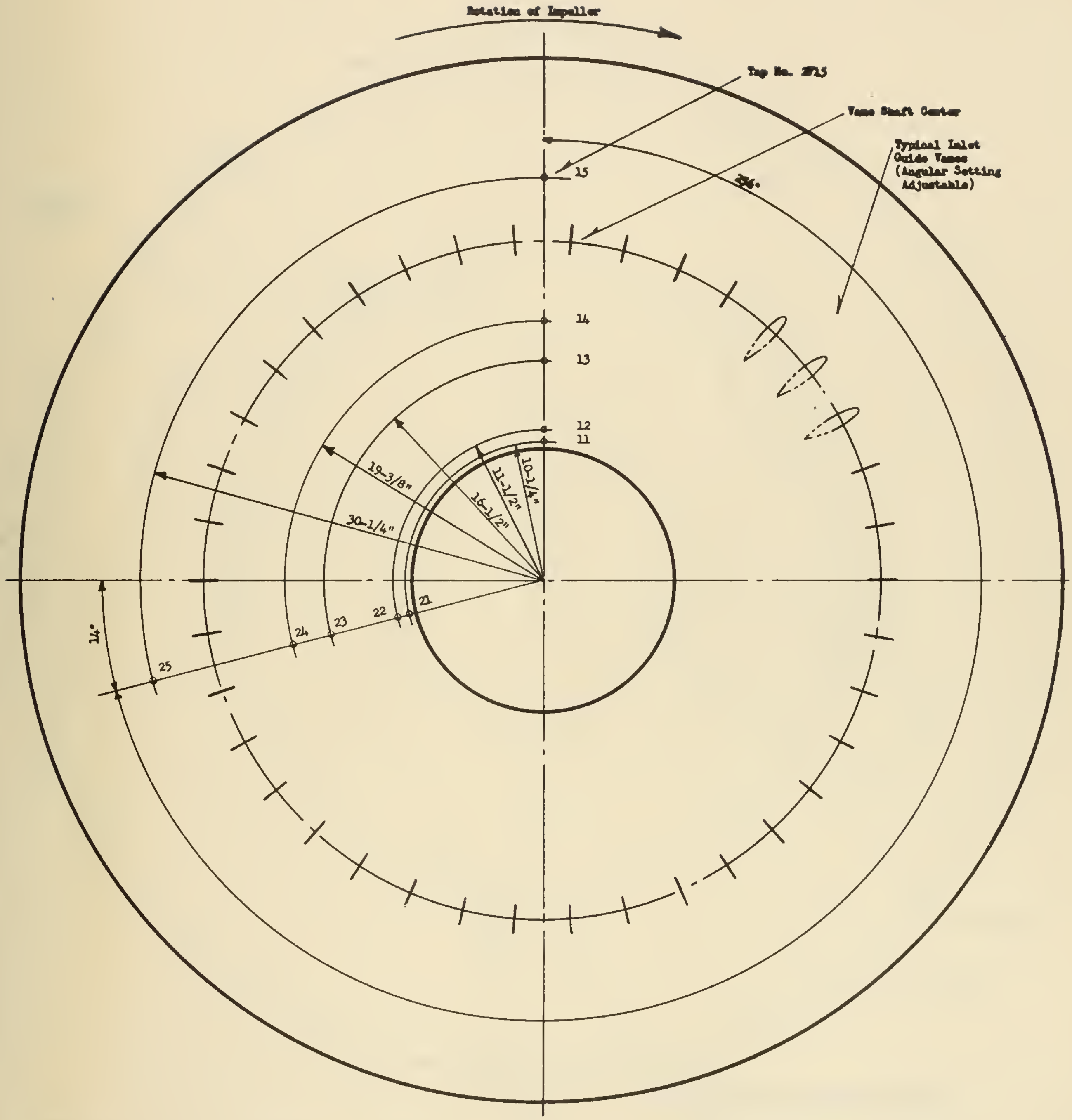
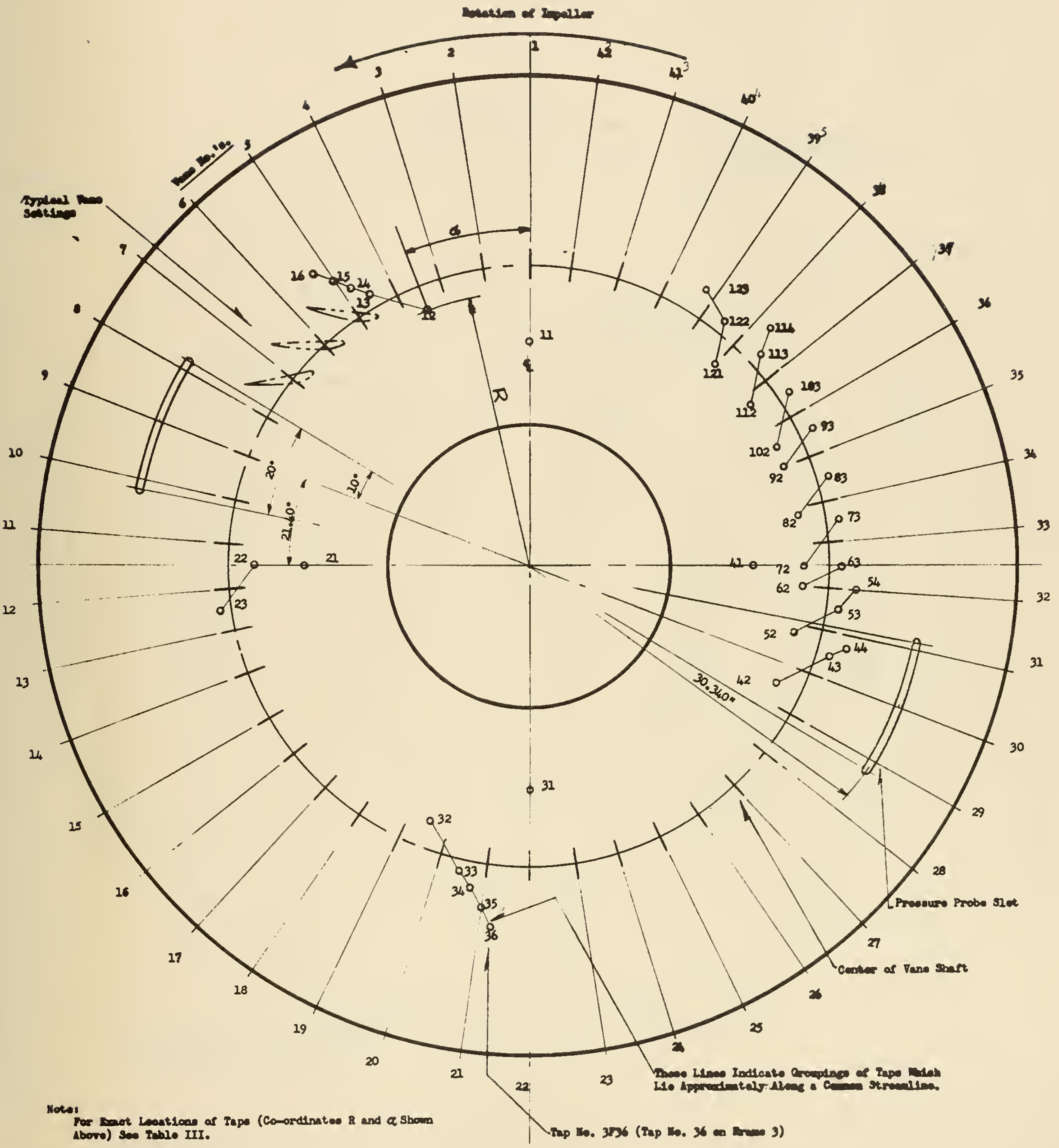


FIG. 14 — WALL PRESSURE TAPS AT FRAME NO. 2



Note:
For Exact Locations of Taps (Co-ordinates R and α Shown Above) See Table III.

FIG. 15 — WALL PRESSURE TAPS AT FRAME NO. 3

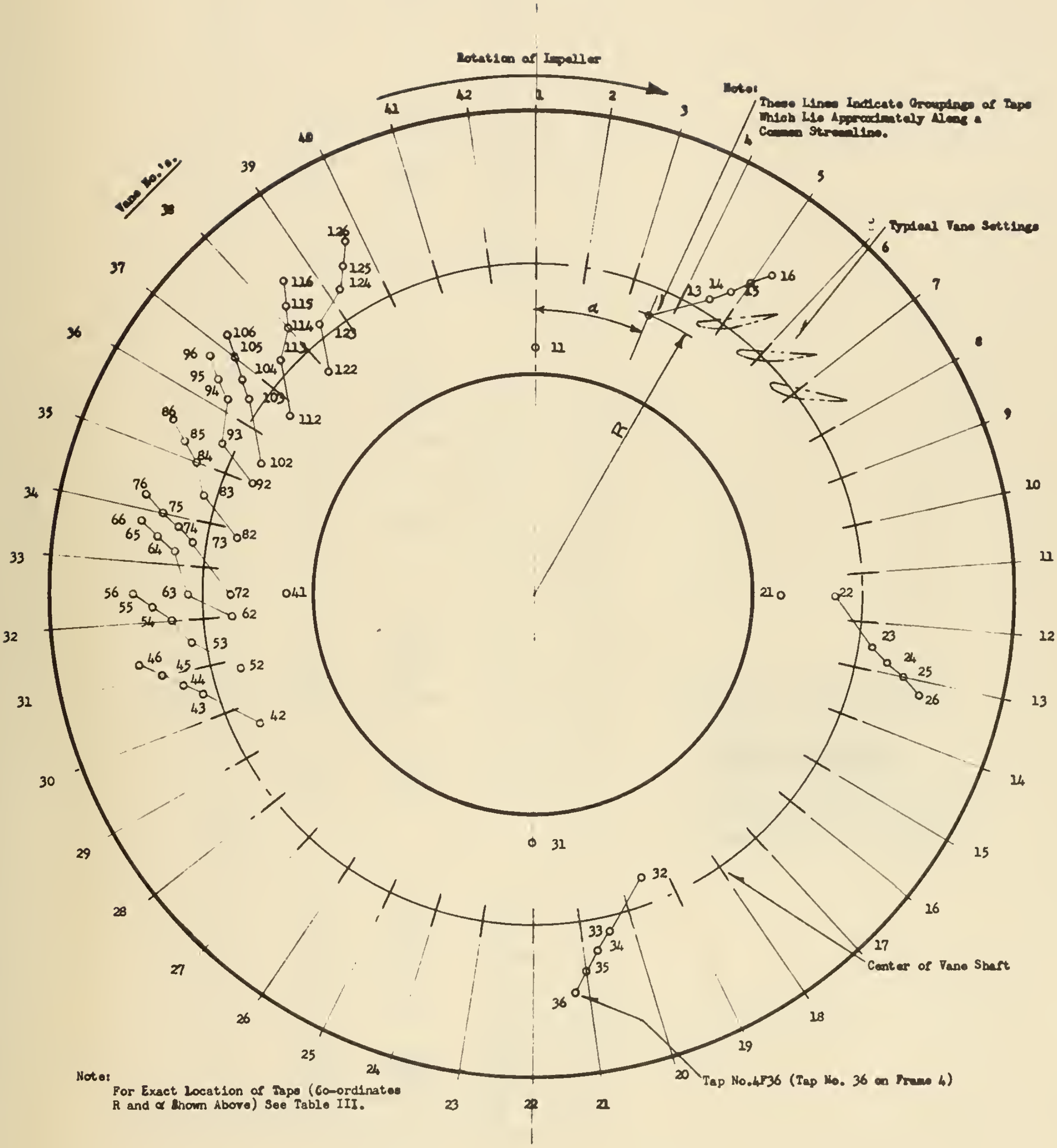
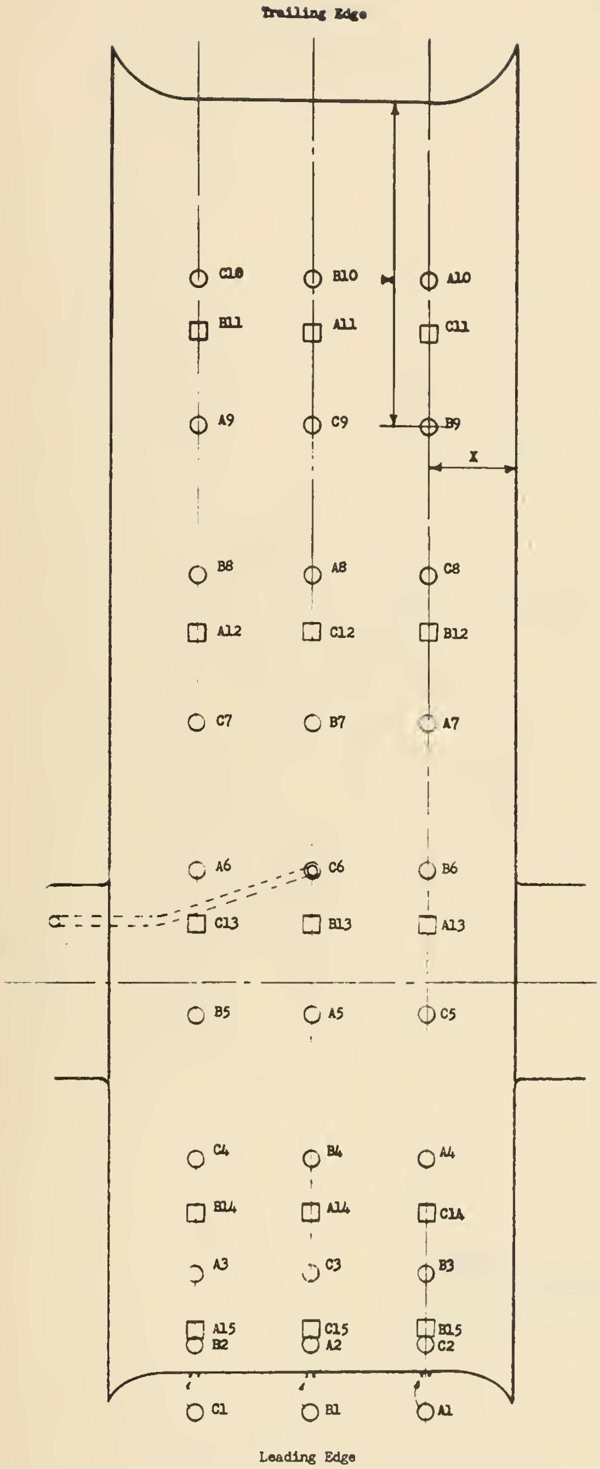


FIG. 16 — WALL PRESSURE TAPS AT FRAME NO. 4



□ = Tap on Pressure Side of Vane
○ = Tap on Suction Side of Vane

A Applies to Vanes 31, 34, 37.
B Applies to Vanes 32, 35, 38.
C Applies to Vanes 33, 36, 39.

The Numbers Shown are Tabbed on the Leads on the Outside of the Machine.

For Exact Locations of Taps See Table II.

FIG. 17 — PRESSURE TAP NUMBERING SYSTEM FOR DIFFUSER VANES

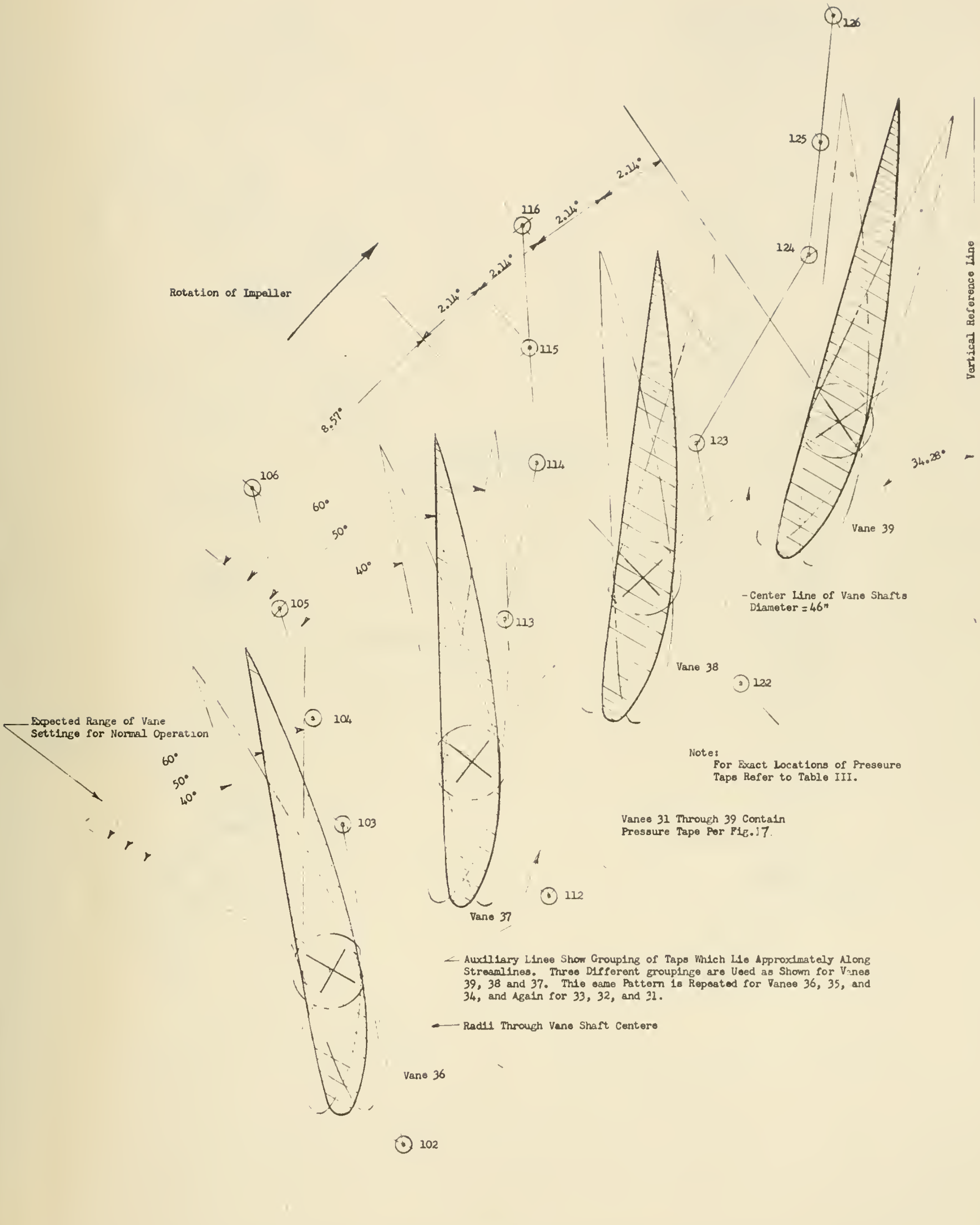


FIG. 18 — WALL PRESSURE TAPS NEAR DIFFUSER VANES AT FRAME NO. 4

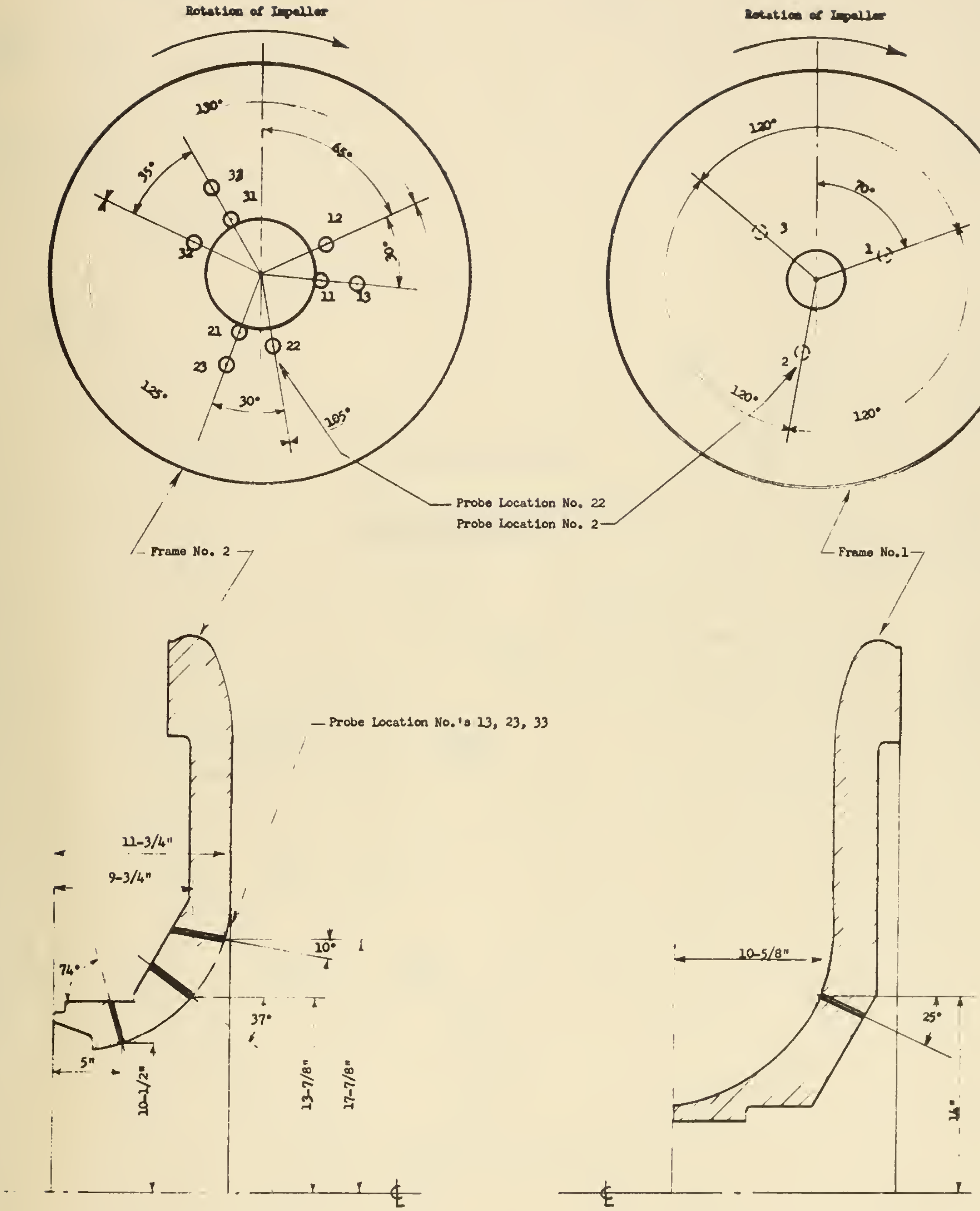


FIG. 19 — PRESSURE PROBE INSTALLATIONS

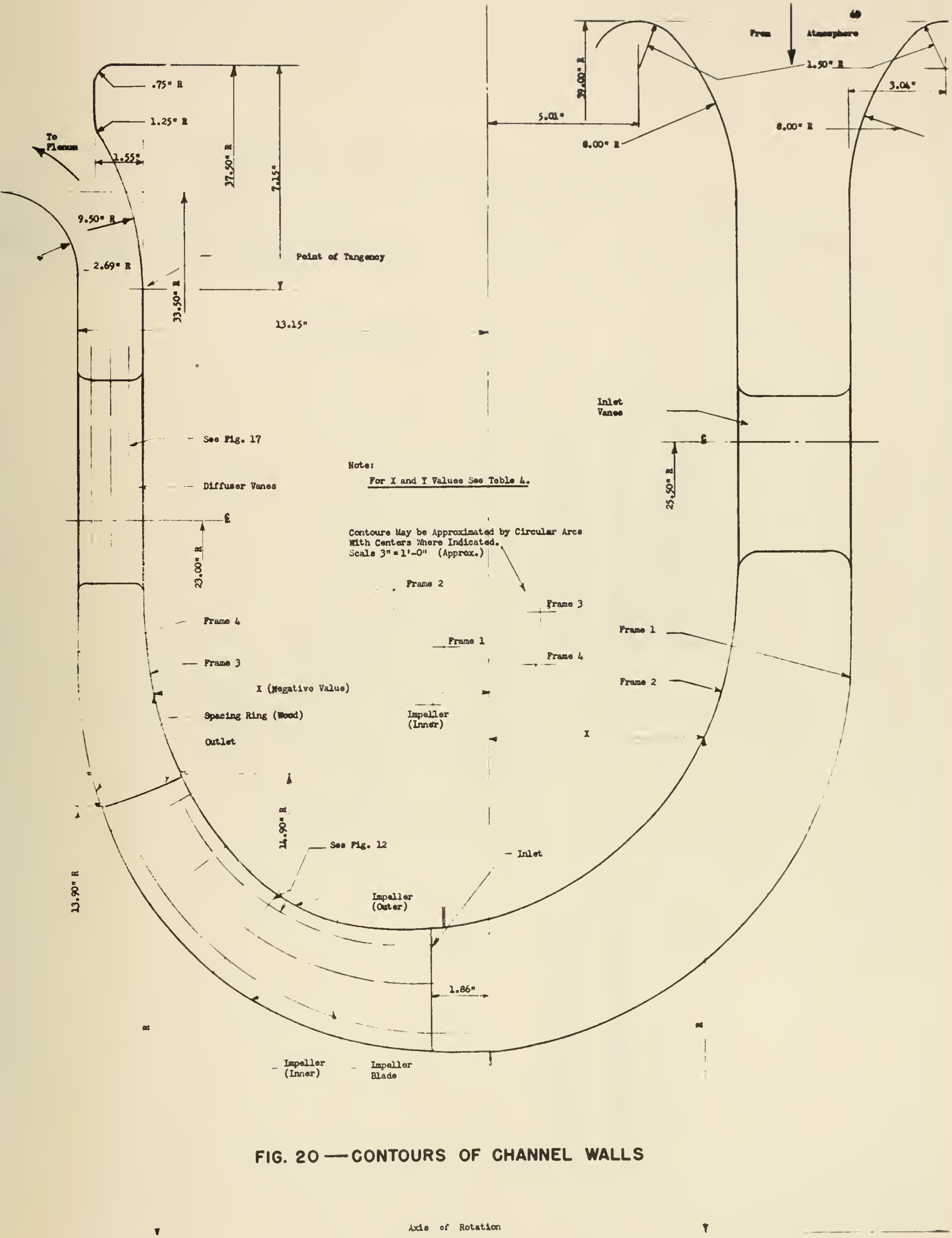
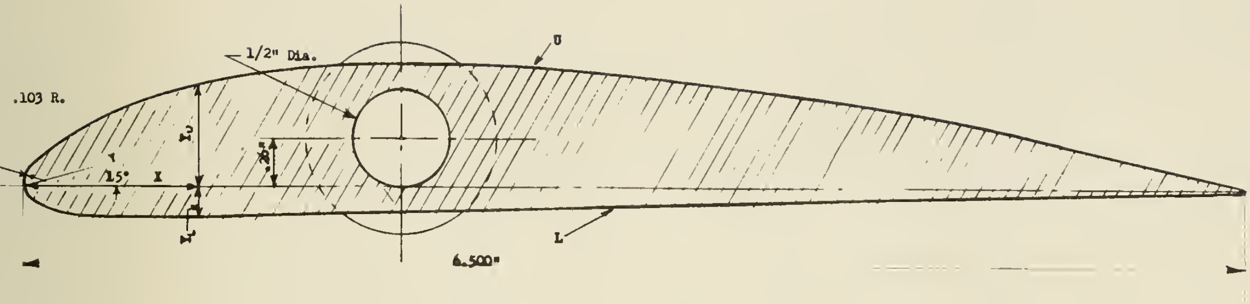


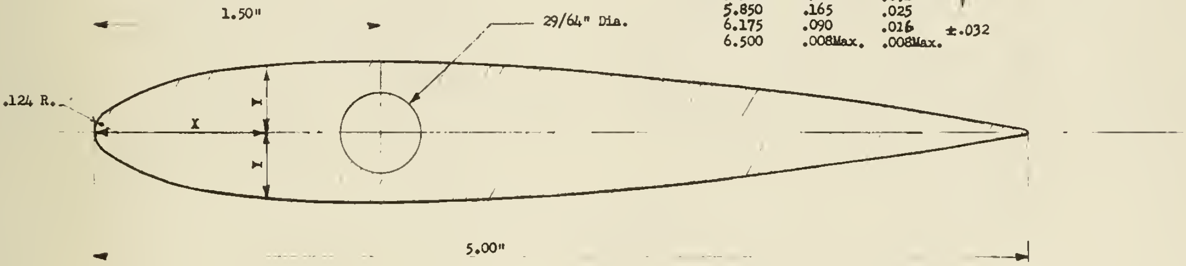
FIG. 20 — CONTOURS OF CHANNEL WALLS



Diffuser Vane (N.A.C.A. 4312)

Contour Chart

X	Y_U	Y_L	Y_U & Y_L Tolerance
.081	.172	.084	±.032
.163	.236	.114	
.325	.332	.142	
.488	.405	.152	
.650	.463	.155	
.975	.550	.150	
1.300	.608	.141	
1.625	.639	.135	
1.950	.650	.130	
2.600	.634	.122	
3.250	.584	.105	
3.900	.511	.083	
4.550	.416	.062	
5.200	.301	.042	
5.850	.165	.025	
6.175	.090	.016	±.032
6.500	.008Max.	.008Max.	



Inlet Guide Vane (N.A.C.A. 0015)

Contour Chart

X	Y	Y (Tolerance)
.062	.118	± .032
.125	.163	
.250	.222	
.375	.262	
.500	.293	
.750	.334	
1.000	.359	
1.250	.371	
1.500	.375	
2.000	.363	
2.500	.331	
3.000	.285	
3.500	.229	
4.000	.164	
4.500	.090	
4.750	.050	± .032
5.000	.008Max.	

FIG. 21 — AIRFOIL SECTIONS OF INLET AND DIFFUSER VANES

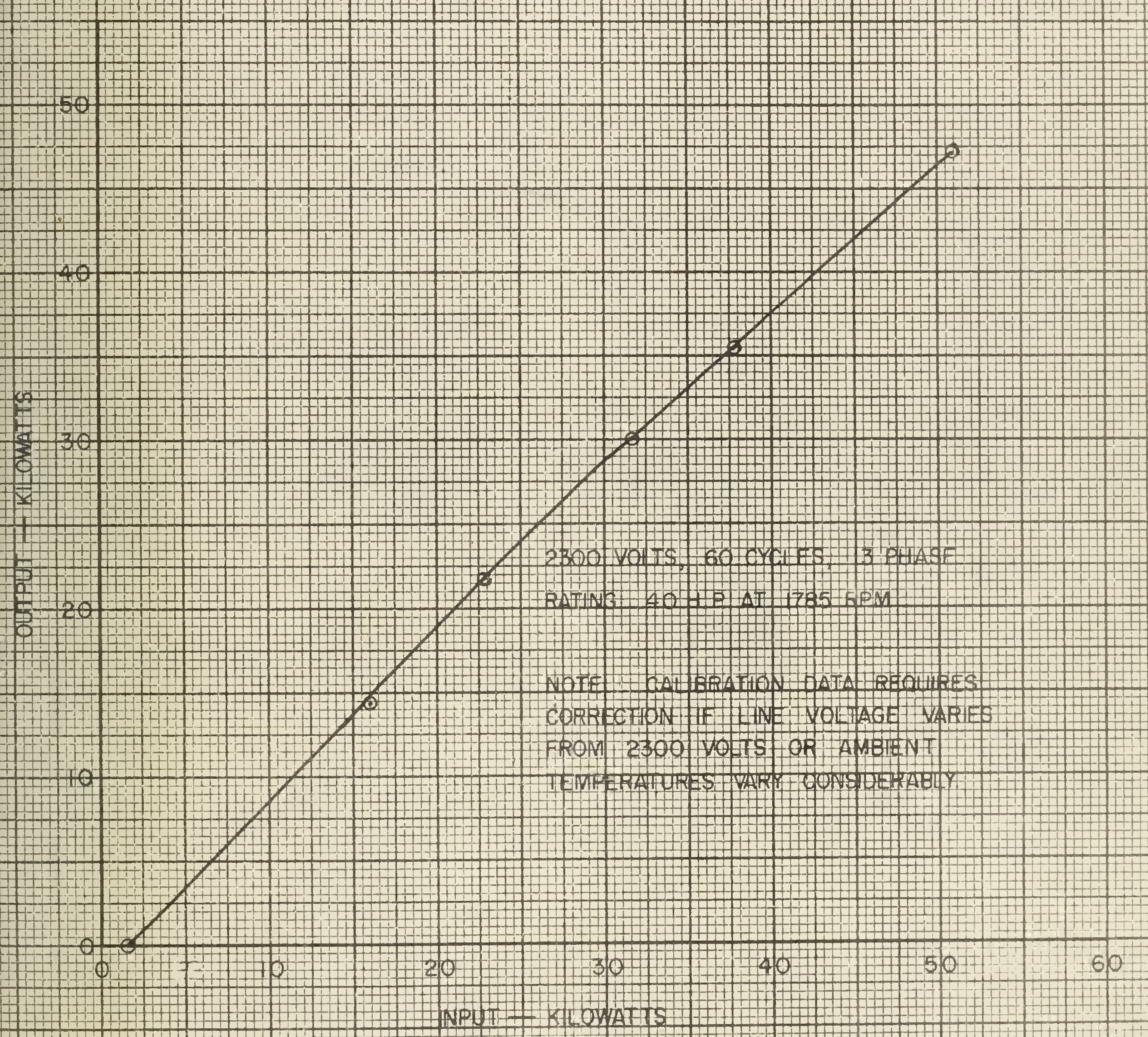


FIG 23 - INPUT - OUTPUT CALIBRATION CURVE OF MOTOR

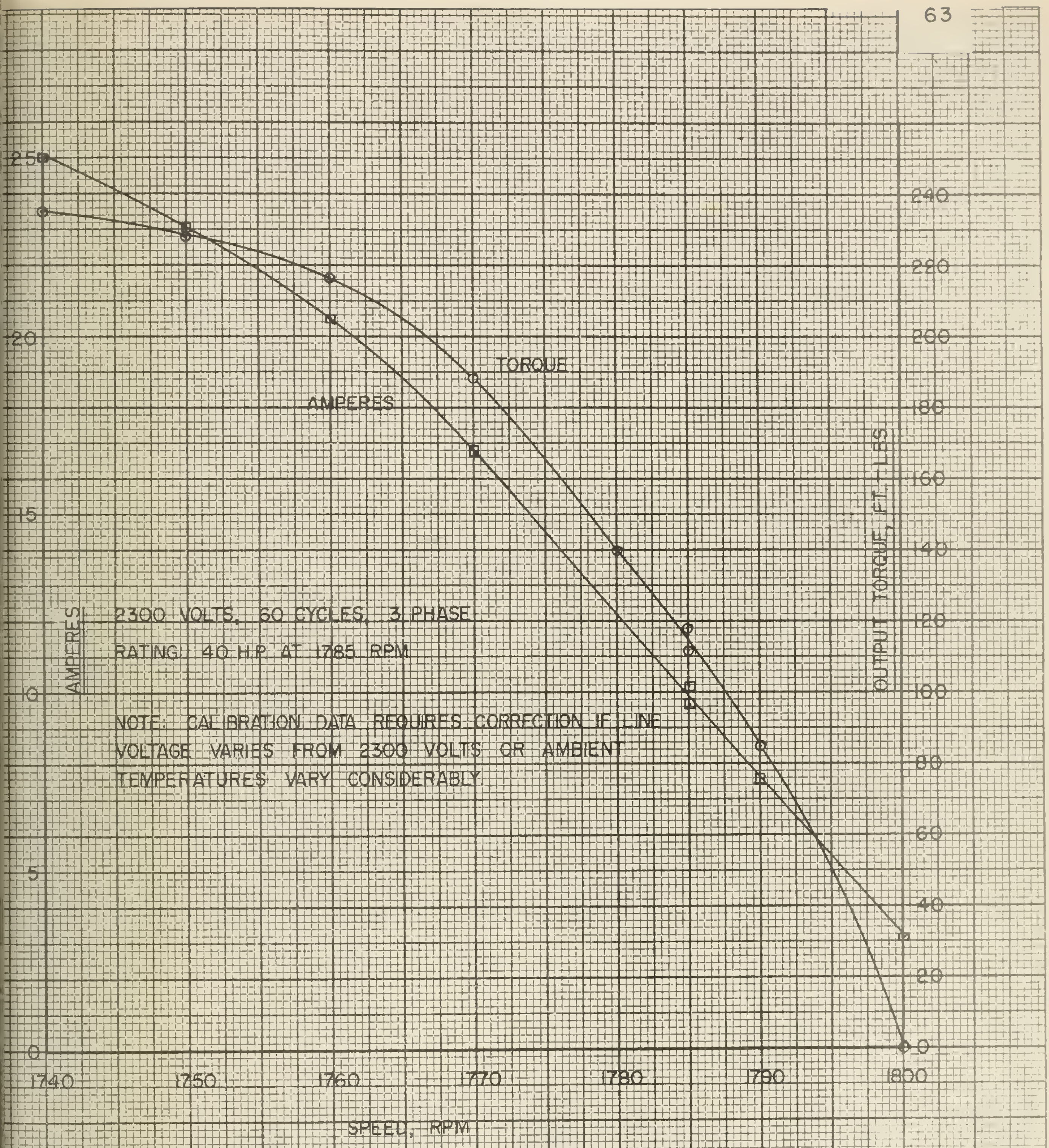


FIG 22

SPEED—TORQUE AND SPEED— AMPERE CALIBRATION CURVES OF MOTOR

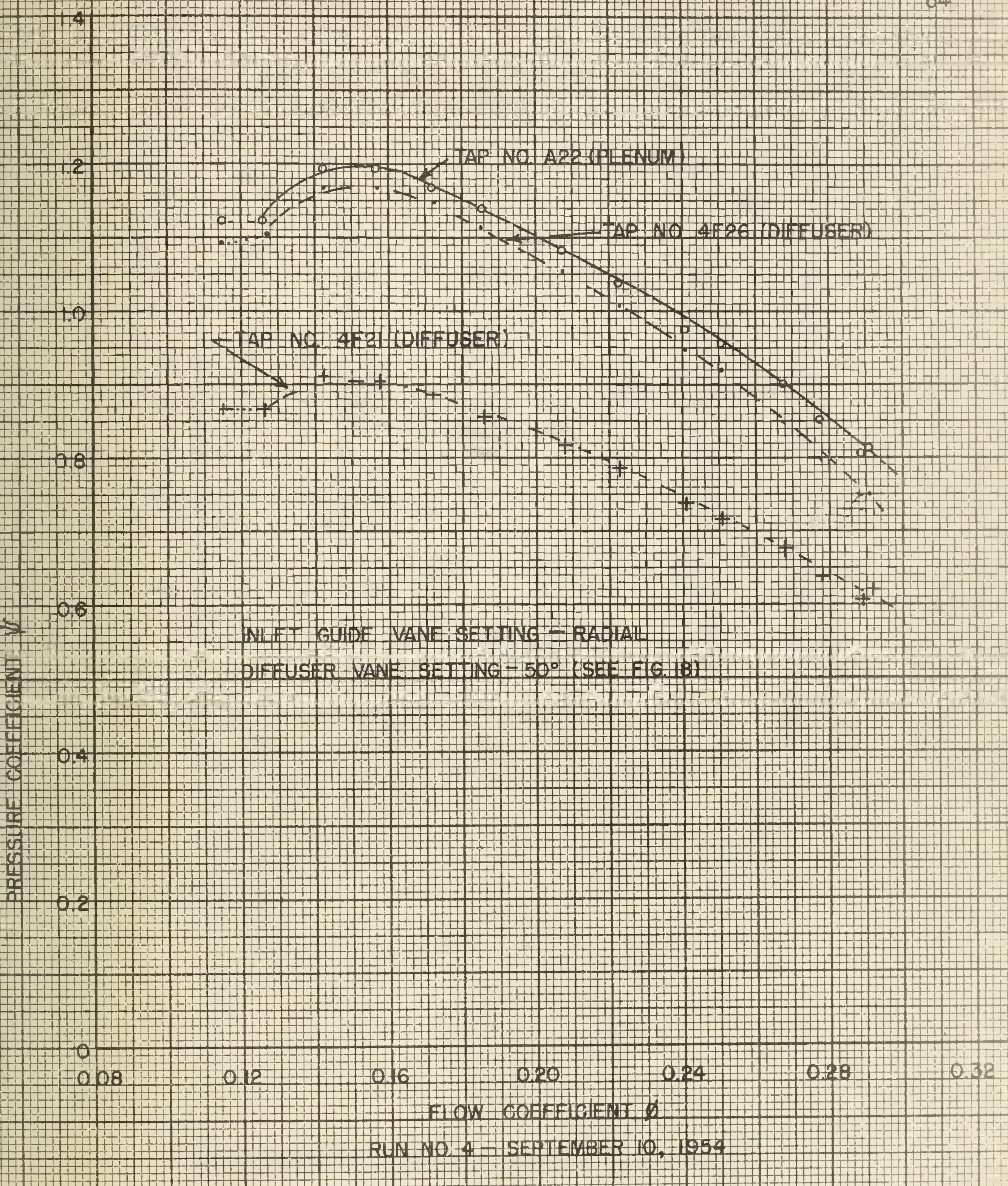


FIG. 24 – OVERALL PERFORMANCE CHARACTERISTICS

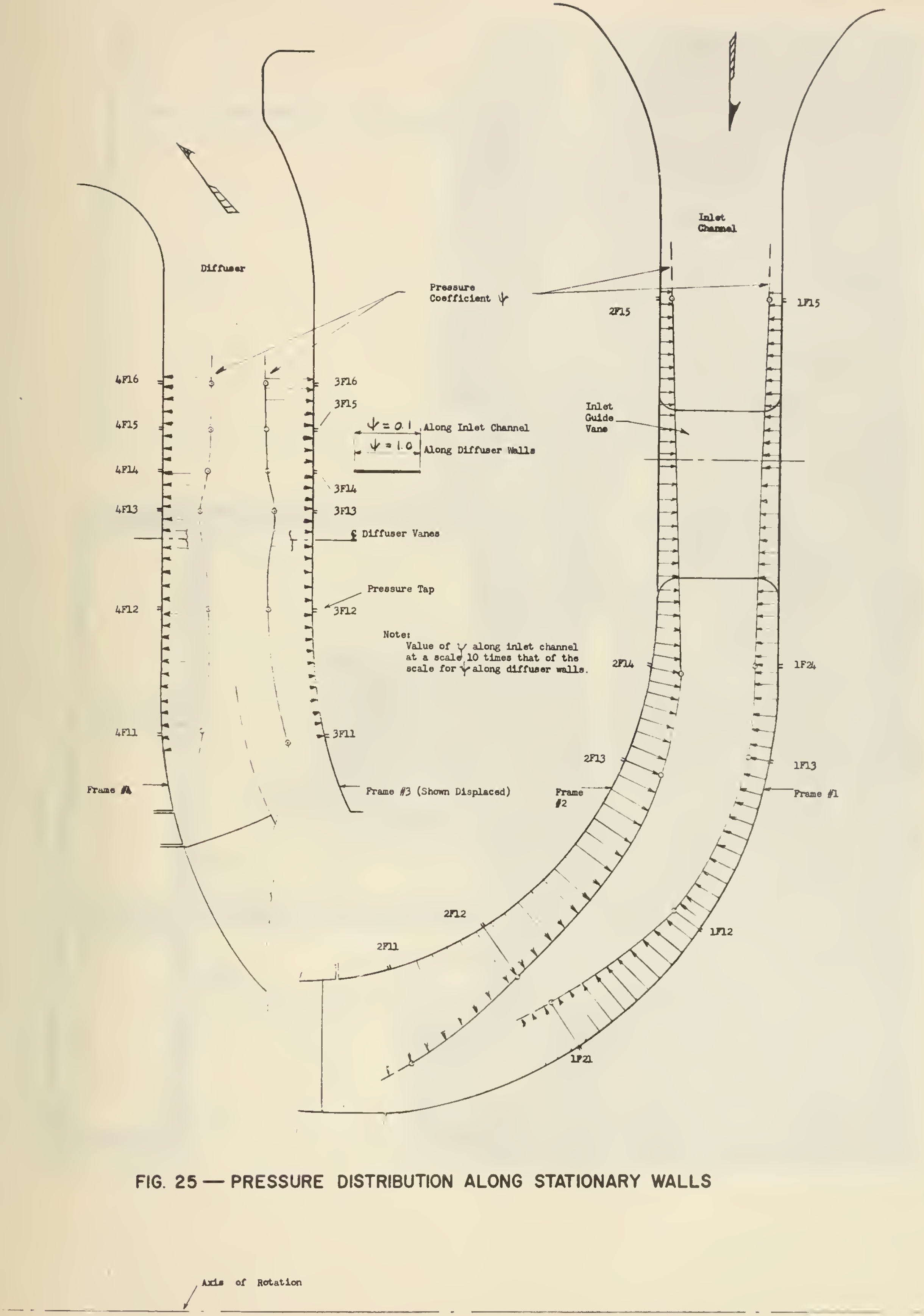


FIG. 25 — PRESSURE DISTRIBUTION ALONG STATIONARY WALLS

FIG. 26 COMPUTATION CENTER, U. S. NAVAL POSTGRADUATE SCHOOL

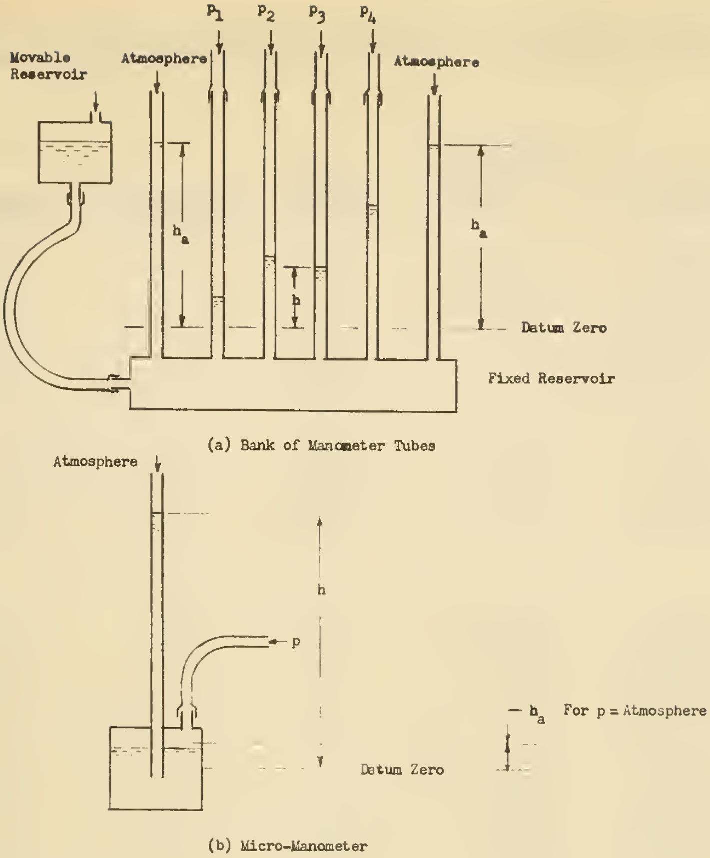


FIG. 27 — MANOMETERS

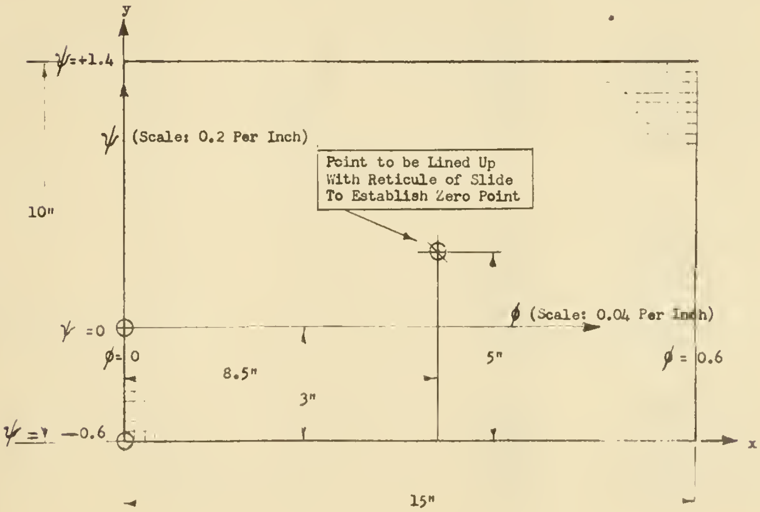


FIG. 28 — ARRANGEMENT OF GRAPH OF ψ VS ϕ FOR DIGITAL PLOTTER

TABLE I - PRESSURE TAP LOCATIONS ON IMPELLER BLADES*

Tap No.	Stream-line	Normal	Quadrant	Blade Letter	Pressure or Suction Side	Co-ordinates R(in.)	X(in.)	Manometer No.
1P21	Mean	1	1	D	P.S.	8.305	2.895	6
1P12	Hub	2	1	D	P.S.	7.700	5.990	2**
1P13	Hub	3	1	D	P.S.	9.235	8.535	1
1P35	Tip	5	1	D	P.S.	14.240	9.720	3
1S21	Mean	1	1	E	S.S.	8.250	2.765	8
1S12	Hub	2	1	E	S.S.	7.570	5.940	5
1S13	Hub	3	1	E	S.S.	9.045	8.580	4
1S35	Tip	5	1	E	S.S.	14.035	9.970	7
2P11	Hub	1	2	J	P.S.	6.785	2.985	6
2P33	Tip	3	2	J	P.S.	10.880	6.880	1
2P34	Tip	4	2	J	P.S.	12.520	8.630	2
2P25	Mean	5	2	J	P.S.	13.910	10.440	3
2S11	Hub	1	2	K	S.S.	6.755	2.740	8
2S33	Tip	3	2	K	S.S.	10.730	6.980	4
2S34	Tip	4	2	K	S.S.	12.470	8.680	5
2S25	Mean	5	2	K	S.S.	13.620	10.685	7
3P32	Tip	2	3	P	P.S.	9.680	5.000	3
3P23	Mean	3	3	P	P.S.	10.320	7.565	2
3P24	Mean	4	3	P	P.S.	12.040	9.365	4
3P15	Hub	5	3	P	P.S.	13.590	11.320	1
3S32	Tip	2	3	Q	S.S.	9.710	4.995	7
3S23	Mean	3	3	Q	S.S.	10.080	7.590	5
3S24	Mean	4	3	Q	S.S.	11.755	9.530	8
3S15	Hub	5	3	Q	S.S.	13.225	11.620	6
4P31	Tip	1	4	U	P.S.	9.225	2.720	5
4P22	Mean	2	4	U	P.S.	8.660	5.370	2
4P23	Mean	3	4	U	P.S.	10.100	7.540	1**
4P14	Hub	4	4	U	P.S.	11.515	10.250	3
4S31	Tip	1	4	V	S.S.	9.370	2.665	8
4S22	Mean	2	4	V	S.S.	8.710	5.280	6**
4S23	Mean	3	4	V	S.S.	9.955	7.595	4
4S14	Hub	4	4	V	S.S.	11.170	10.370	7

*Refer to Fig. 12
**Tube plugged

[illegible]

TABLE II - VANE PRESSURE TAP LOCATIONS***

VANE 31			VANE 34			VANE 37		
No.	X	Y	No.	X	Y	No.	X	Y
**1	0.40	6.50	1	0.39	6.50	1	0.41	6.50
2	1.02	6.32	2	1.02	6.32	2	1.03	6.31
3	1.64	5.97*	3	1.62	5.97*	3	1.64	5.97*
4	0.41	5.36	4	0.41	5.33	4	0.41	5.35
5	1.03	4.62	5	1.00	4.60	5	1.03	4.62
6	1.66	3.82	6	1.60	3.88	6	1.66	3.85
7	0.41	3.10	7	0.32*	3.25*	7	0.42	3.10
8	1.03	2.36	8	1.02	2.34	8	1.05	2.38
9	1.64	1.60	9	1.62	1.60	9	1.66	1.63
10	0.41	0.85	10	0.39	0.83	10	0.42	0.85
11	1.03	1.14	11	1.00	1.17	11	1.04	1.12
12	1.64	2.66	12	1.62	2.67	12	1.63	2.67
13	0.42	4.17	13	0.42	4.17	13	0.44	4.20
14	1.02	5.72	14	1.02	5.69	14	1.02	5.70
15	1.66	6.25	15	1.65	6.30	15	1.62	6.27

VANE 32			VANE 35			VANE 39		
**1	1.02	6.50	1	1.02	6.50	1	1.02	6.50
2	1.62	6.29*	2	1.62	6.29	2	1.66	6.30
3	0.41	5.97	3	0.41	5.97	3	0.44	5.97
4	1.03	5.34	4	1.03	5.32	4	1.03	5.32
5	1.65	4.61	5	1.67	4.60	5	1.66	4.62
6	0.41	3.85	6	0.41	3.84	6	0.42	3.85
7	1.03	3.10	7	1.04	3.09	7	1.05	3.10
8	1.63	2.33	8	1.65	2.33	8	1.66	2.36
9	0.41	1.61	9	0.41	1.60	9	0.42	1.60
10	1.02	0.83	10	1.02	0.83	10	1.03	0.83
11	1.64	1.13	11	1.64	1.14	11	1.65	1.15
12	0.42	2.67	12	0.44	2.66	12	0.44	2.67
13	1.04	4.18	13	1.05	4.18	13	1.06	4.19
14	1.65	5.70	14	1.65	5.69	14	1.65	5.72
15	0.44	6.26	15	0.44	6.26	15	0.44	6.27

*These values require rechecking.

**Tap No. 1 on each of the following vanes is below the leading edge by the amount indicated:

Vane 31 - 1/64" Vane 32 - 1/32"
Vane 34 - 1/16" Vane 35 - 1/32"
Vane 37 - 1/32"

***Measured locations of pressure taps differ from design values given on next page because of manufacturing discrepencies.

TABLE II - VANE PRESSURE TAP LOCATIONS
(Concluded)

VANE 33			VANE 36			VANE 39		
No.	X	Y	No.	X	Y	No.	X	Y
1	1.62	6.50	1	1.61	6.50	1	1.62	6.50
2	0.41	6.38	2	0.41	6.32	2	0.42	6.32
3	1.03	5.97	3	1.03	5.97	3	1.05	5.97
4	1.64	5.35	4	1.64	5.35	4	1.66	5.35
5	0.42	4.67	5	0.41	4.62	5	0.42	4.62
6	1.05	3.85	6	1.05	3.84	6	1.05	3.84
7	1.66	3.11	7	1.66	3.10	7	1.65	3.11
8	0.44	2.38	8	0.43	2.35	8	0.43	2.35
9	1.05	1.60	9	1.05	1.60	9	1.04	1.60
10	1.66	0.86	10	1.67	0.85	10	1.66	0.85
11	0.44	1.15	11	0.44	1.15	11	0.42	1.13
12	1.05	2.67	12	1.05	2.69	12	1.05	2.68
13	1.66	4.19	13	1.67	4.19	13	1.67	4.19
14	0.44	5.70	14	0.44	5.69	14	0.44	5.69
15	1.04	6.25	15	1.03	6.26	15	1.05	6.26

DESIGN LOCATIONS

No.	X Vanes 31,34,37	X Vanes 32,35,38	X Vanes 33,36,39	Y All Vanes
1	0.44	1.04	1.64	6.50
2	1.04	1.64	0.44	6.35
3	1.64	0.44	1.04	6.00
4	0.44	1.04	1.64	5.40
5	1.04	1.64	0.44	4.65
6	1.64	0.44	1.04	3.90
7	0.44	1.04	1.64	3.15
8	1.04	1.64	0.44	2.40
9	1.64	0.44	1.04	1.65
10	0.44	1.04	1.64	0.90
11	1.04	1.64	0.44	1.20
12	1.64	0.44	1.04	2.70
13	0.44	1.04	1.64	4.20
14	1.04	1.64	0.44	5.70
15	1.64	0.44	1.04	6.30

TABLE III - WALL PRESSURE TAP LOCATIONS ON FRAMES 3 AND 4

Tap No. Frame 4	R(In.)	α Degrees	Tap No. Frame 3	Tap No. Frame 4	R(In.)	α Degrees	Tap No. Frame 3
11	17.25	00.0	11				
12	21.00	21.4	12	72	21.00	270.0	72
13	23.94	30.0	13	73	23.94	278.6	73
14	25.12	32.1	14	74	25.12	280.7	None
15	26.37	34.2	15	75	26.37	282.8	None
16	27.75	36.4	16	76	27.75	285.0	None
21	17.25	90.0	21				
22	21.00	90.0	22	82	21.00	280.7	82
23	23.94	98.6	23	83	23.94	287.1	83
24	25.12	100.7	None	84	25.12	291.4	None
25	26.37	102.9	None	85	26.37	293.6	None
26	27.75	105.0	None	86	27.75	295.7	None
31	17.25	180.0	31				
32	21.00	158.6	32	92	21.00	291.4	92
33	23.94	167.1	33	93	23.94	295.7	93
34	25.12	169.2	34	94	25.12	302.1	None
35	26.37	171.4	25	95	26.37	304.3	None
36	27.75	173.6	36	96	27.75	306.4	None
41	17.25	270.0	41				
42	21.00	244.3	42	102	21.00	295.7	102
43	23.94	252.9	43	103	23.94	304.3	103
44	25.12	255.0	44	104	25.12	306.4	None
45	26.37	257.1	None	105	26.37	308.6	None
46	27.75	259.3	None	106	27.75	310.7	None
52	21.00	255.0	52	112	21.00	306.4	112
53	23.94	261.4	53	113	23.94	312.9	113
54	25.12	265.7	54	114	25.12	317.1	114
55	26.37	267.9	None	115	26.37	319.3	None
56	27.75	270.0	None	116	27.75	321.4	None
62	21.00	265.7	62	122	21.00	317.1	122
63	23.94	270.0	63	123	23.94	321.4	123
64	25.12	276.4	None	124	25.12	327.9	124
65	26.37	278.6	None	125	26.37	330.0	None
66	27.75	280.7	None	126	27.75	332.1	None

TABLE IV - CO-ORDINATES OF CHANNEL WALLS

Hub Streamline

Frame 1

X	R
11.71	20.50
11.69	20.00
11.68	19.50
11.66	19.00
11.64	18.50
11.60	18.00
11.56	17.50
11.50	17.00
11.42	16.50
11.30	16.00
11.20	15.50
11.06	15.00
10.89	14.50
10.71	14.00
10.59	13.50
10.26	13.00
10.00	12.50
9.70	12.00
9.38	11.50
9.01	11.00
8.62	10.50
8.17	10.00
8.04	9.87
7.54	9.34
7.04	8.93
6.54	8.53
6.04	8.18
5.54	7.85
5.04	7.55
4.54	7.29
4.04	7.05
3.54	6.85
3.04	6.65
2.54	6.48
2.04	6.32
1.54	6.18
1.04	6.07
.54	5.98
.04	5.92

Impeller

X	R
.00	5.97
-.50	5.94
-1.00	5.92
-1.50	5.93
-2.00	5.96
-2.50	6.00
-3.00	6.06
-3.50	6.13
-4.00	6.24
-4.50	6.36
-5.00	6.51
-5.50	6.68
-6.00	6.88
-6.50	7.10
-7.00	7.36
-7.50	7.65
-8.00	7.98
-8.50	8.35
-9.00	8.76
-9.50	9.22
-10.00	9.73
-10.23	10.00
-10.62	10.50
-10.98	11.00
-11.29	11.50
-11.58	12.00
-11.84	12.50
-12.07	13.00
-12.27	13.50
-12.45	14.00

Frame 4

X	R
-12.70	14.98
-12.81	15.50
-12.90	16.00
-12.96	16.50
-13.02	17.00
-13.06	17.50
-13.09	18.00
-13.12	18.50
-13.14	19.00
-13.15	19.50

Tip Streamline

Frame 2

X	R
8.05	22.50
8.04	22.00
8.04	21.50
8.02	21.00
7.99	20.50
7.96	20.00
7.90	19.50
7.83	19.00
7.73	18.50
7.62	18.00
7.48	17.50
7.32	17.00
7.14	16.50
6.93	16.00
6.68	15.50
6.40	15.00
6.08	14.50
5.72	14.00
5.30	13.50
4.84	13.00
4.56	12.74
4.06	12.30
3.56	11.92
3.06	11.57
2.56	11.27
2.06	11.00
1.56	10.76
1.06	10.57
.56	10.39
.06	10.25
-.44	10.12
-.94	10.03
-1.44	9.98

Impeller

X	R
-1.50	9.94
-2.00	9.92
-2.50	9.90
-3.00	9.91
-3.50	9.94
-4.00	9.99
-4.50	10.07
-5.00	10.19
-5.50	10.36
-6.00	10.57
-6.50	10.86
-7.00	11.21
-7.50	11.63
-8.00	12.11
-8.34	12.50
-8.73	13.00
-9.08	13.50
-9.38	14.00
-9.64	14.50
-9.88	15.00

Frame 3

X	R
-9.90	14.98
-10.12	15.50
-10.29	16.00
-10.46	16.50
-10.59	17.00
-10.71	17.50
-10.80	18.00
-10.87	18.50
-10.93	19.00
-10.98	19.50
-11.02	20.00
-11.04	20.05
-11.06	21.00
-11.07	21.50

TABLE V - PRESSURE COEFFICIENTS ALONG IMPELLER BLADES FROM INITIAL TESTS*

Flow Coeff. ϕ	**Tap No.	Pressure Coefficients ψ 1P21	1S21	1P12	1S12
0.3320		-0.1256	-0.2354	-0.0935	-0.1614
0.2988		-0.0712	-0.2064	-0.0681	-0.1105
0.2538		+0.0522	-0.0539	+0.0553	+0.0128
0.1884		+0.1459	+0.0586	+0.1351	+0.1036
0.1492		+0.1538	+0.0368	+0.1315	+0.1036
0.3312		-0.1256	-0.2354	-0.0935	-0.1614

Flow Coeff. ϕ	**Tap No.	Pressure Coefficients ψ 1P13	1S13	1P35	1S35
0.3320		+0.0382	+0.0029	+0.6104	+0.4765
0.2988		+0.0636	+0.0356	+0.6358	+0.5346
0.2538		+0.1871	+0.1554	+0.7592	+0.6580
0.1884		+0.2670	+0.2389	+0.8391	+0.7561
0.1492		+0.2633	+0.2353	+0.8391	+0.7633
0.3312		+0.0346	+0.0029	+0.6104	+0.4765

*Data based on Run No. 6. Rotor pressures measured in Quadrant I only.
**For pressure tap locations, see Table I.

TABLE VI - PARAMETERS FOR FLOW MEASUREMENT

Quantity	Units			
D_2	in.	11.5	13.5	15.5
$\frac{A_2}{A_1}$	---	0.24465	0.33715	0.44445
K	---	0.6230	0.6422	0.6742
Q_o	ft^3/sec	600.38	852.87	1180.31
ϕ_o	---	1.55465	2.20846	3.05636
ε	---	0.3078	0.3213	0.3422

Constants		
D_1	in.	23.250
U_o	ft/sec	223.744
A_m	ft^2	1.726
N_o	rpm	1800
P_o	lb/ft^2	2116
T_o	^oR	520
R	$ft/^oR$	53.345
g	ft/sec^2	32.174
γ	---	1.4

TABLE VII - CORRECTION FACTORS $\Delta\Psi$ FOR CENTRIFUGAL EFFECT AT IMPELLER BLADES

Quadrant	Tap No.	Manometer Line	$\Delta\Psi$
1	1P13	1	0.4122
1	1P12	2	0.2841
1	1P35	3	0.9917
1	1S13	4	0.3951
1	1S12	5	0.2743
1	1P21	6	0.3318
1	1S35	7	0.9631
1	1S21	8	0.3273
2	2P33	1	0.5754
2	2P34	2	0.7647
2	2P25	3	0.9459
2	2S33	4	0.5594
2	2S34	5	0.7585
2	2P11	6	0.2187
2	2S25	7	0.9065
2	2S11	8	0.2167
3	3P15	1	0.9025
3	3P23	2	0.5169
3	3P32	3	0.4538
3	3P24	4	0.7065
3	3S23	5	0.4927
3	3S15	6	0.8542
3	3S32	7	0.4566
3	3S24	8	0.6731
4	4P23	1	0.4947
4	4P22	2	0.3615
4	4P14	3	0.6456
4	4S23	4	0.4804
4	4P31	5	0.4113
4	4S22	6	0.3658
4	4S14	7	0.6069
4	4S31	8	0.4246

TABLE VIII - SET-UP FOR FINAL TABLE OF RESULTS

	Flow Coeff.	Pressure Coefficients				
		Y=1	Y=2	Y=3	---	Y=Ymax
X=1	Φ_1	$\Psi_{1,1}$	$\Psi_{1,2}$	---	---	$\Psi_{1,Ymax}$
X=2	Φ_2	$\Psi_{2,1}$	$\Psi_{2,2}$	---	---	$\Psi_{2,Ymax}$
X=3	Φ_3	$\Psi_{3,1}$	$\Psi_{3,2}$	---	---	$\Psi_{3,Ymax}$
---	---	---	---	---	---	---
---	---	---	---	---	---	---
X=Xmax	Φ_{Xmax}	$\Psi_{Xmax,1}$	$\Psi_{Xmax,2}$	---	---	$\Psi_{Xmax,Ymax}$

TABLE IX - MEMORY CONTENTS

Channel	Cells from	Cells to	Contents	Print-out command
00	0000	0077	Program for calculation of Φ	/357f/s
01	0100	0101	" " " " " Φ	
	0110	0127	Temporary storage of Φ (Dec.) and Ψ (Dec.) for input to and output from magnetic tape unit	
	0130	0147	Temporary storage of Φ/10(Oct.) and Ψ/10(Oct.) for plotting	
02	0200	0237	Data storage for calculation of Ψ filled by Flexowriter from data tapes for Ψ. Constants filled by program	
	0240	0255	Auxiliary Commands	
03	0300	0370	Number storage for calculation of Φ	/361f/s
04	0400	0477	Program for calculation of Ψ	/240f/s
05	0500	0571	" " " " " Ψ	
06	0600	0661	Number storage for subroutine for print preparation of final table of results	/254f/s
07	0700	0722	Subroutine: Conversion decimal to octal	/363f/s
	0725	0745	Subroutine: Conversion octal to decimal	/365f/s
	0750	0760	Memory sum check (adds contents of cells 0000 to 1650)	
10	1000	1020	Subroutine: Square root	/367f/s
11	1100	1111	Auxiliary data for calculation of Φ for different orifice dia. Filled by Flexowriter from auxiliary data tapes.	
	1120	1147	Subroutine for plotting Ψ vs. Φ	/244f/s
12	1200	1277	Storage of Φ/10(Oct.) by program for Φ, for use in program for Ψ	/353f/s
13	1300	1371	Number storage for calculation of Ψ	/242f/s
14	1400	1477	Storage of Φ(Dec.) by program for Φ, for use in program for Ψ	/355f/s
15	1500	1503	Auxiliary data for Ψ. Filled by Flexowriter from data tapes for Ψ	
	1504	1536	Subroutine: Print preparation for final table of results	/252f/s
16	1600		Must always be zero	
	1611	1650	Values of $\Delta\Psi$/10(Oct.) for pressure taps of rotor blades	/246f/s
17			Used temporarily for subroutine no. 101 (Readings cards with IBM Machine)	

TABLE X - CODE R FOR PRESSURE TAPS ON IMPELLER BLADES

Quadrant	Tap No.	Manometer Line	Code R
1	1P13	1	11f
1	1P12	2	12f
1	1P35	3	13f
1	1S13	4	14f
1	1S12	5	15f
1	1P21	6	16f
1	1S35	7	17f
1	1S21	8	20f

Quadrant	Tap No.	Manometer Line	Code R
2	2P33	1	21f
2	2P34	2	22f
2	2P25	3	23f
2	2S33	4	24f
2	2S34	5	25f
2	2P11	6	26f
2	2S25	7	27f
2	2S11	8	30f

Quadrant	Tap No.	Manometer Line	Code R
3	3P15	1	31f
3	3P23	2	32f
3	3P32	3	33f
3	3P24	4	34f
3	3S23	5	35f
3	3S15	6	36f
3	3S32	7	37f
3	3S24	8	40f

Quadrant	Tap No.	Manometer Line	Code R
4	4P23	1	41f
4	4P22	2	42f
4	4P14	3	43f
4	4S23	4	44f
4	4P31	5	45f
4	4S22	6	46f
4	4S14	7	47f
4	4S31	8	50f